A HYBRID APPROACH FOR SELECTING MATERIAL HANDLING EQUIPMENT IN WAREHOUSE

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by

THOMY EKO SAPUTRO

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A HYBRID APPROACH FOR SELECTING MATERIAL HANDLING EQUIPMENT IN WAREHOUSE

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Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

Prof. Dr. Ibrahim Akman

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I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

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I declare and guarantee that all data, knowledge and information in this document has been obtained, processed and presented in accordance with academic rules and ethical conduct. Based on these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

A Hybrid Approach For Selecting Material Handling in Warehouse

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Warehouse operations is very closely related to material handling activities. Loading, unloading, transporting and picking material take a huge part of the activities. To handle material properly as well as contributing value to the material, operator and environment, material handling equipment (MHE) is required. The selection of a proper MHE needs an effort since consideration is linked to mutli-criteria and multi-objective decision making problem. Here, a hybrid method namely integration of entropy based-hierarchical fuzzy TOPSIS and MOMILP is proposed to MHE selection problem for seeking the best alternative. Alternative is evaluated based on the criteria which are determined according to subjective and objective criteria. subjective weight is derived from fuzzy AHP. To deal with objective criteria, Entropy method is adopted to determine the weight. Alternative evaluation is conducted by using fuzzy TOPSIS. For final execution of the selection, MOMILP model is developed incorporating two goals, which are, to minimize disadvantage of use and to minimize total cost of material handling. Augmented e-contraint method (AUGMECON) is used to solve the model. A case study is given to illustrate the method. The results show the effectiveness of the hybrid method in a complex decision making.

Keywords: MHE selection, warehouse operations, fuzzy logic, entropy, MCDM, MOMILP

ÖZ

Depo Malzeme ele seçilmesi için Hibrit Yaklaşım

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Yüksek Lisans, Endüstri Mühendisliği Bölümü

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Depo operasyonları çok yakından elleçleme faaliyetleri ile ilgilidir.. Yükleme, boşaltma, malzeme taşıma ve toplama faaliyetlerinin büyük bir kısmını alır. Düzgün de malzeme, operatör ve çevre, malzeme elleçleme ekipmanları (MEE) değer katkı olarak gerekli malzemeyi işlemek için. Göz Tk-kriterler ve çok objektif karar verme sorunu ile bağlantılı olduğundan uygun bir mhe seçimi bir çaba gerekiyor. Burada, entropi tabanlı-hiyerarşik bulanık TOPSIS ve MOMILP bir melez bir yöntem yani entegrasyonu en iyi alternatif arayan için MEE seçim problemine önerilmiştir. Alternatif subjektif ve objektif kriterlere göre belirlenen kriterlere göre değerlendirilir. subjektif ağırlığı bulanık AHP türetilmiştir. Objektif kriterler ile başa çıkmak için, Entropi yöntemi ağırlığını belirlemek için benimsenmiştir. Alternatif değerlendirme bulanık TOPSIS kullanılarak yapılır. Seçimin son yürütülmesi için, MOMILP modeli kullanım dezavantajı en aza indirmek ve malzeme taşıma toplam maliyetini en aza indirmek için iki hedefleri, birleştiren geliştirilmiştir. Augmented e-contraint yöntemi (AUGMECON) modelini çözmek için kullanılır. Bir vaka çalışması yöntemini göstermek için verilir. Sonuçlar karmaşık bir karar verme hibrit yöntemin etkinliğini göstermektedir.

Anahtar Kelimeler: MEE seçimi, depo işlemleri, fuzzy logic, entropi ağırlık, MCDM, MOMILP

DEDICATION

I specially present this THESIS to My Father, Gholib and My Mother, Reni. The spirit and passion on the accomplishment of this thesis is merely inspired from them.

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I express sincere appreciation to my supervisor Assoc.Prof.Dr. Babek Erdebilli for his guidance and insight throughout the research. To my parents, thank you very much for the endless prayer in every single day for the success of my study. I gladly send the best greeting to Mr. Umar Badar Rifa'i as a warehouse supervisor of PLI to allow me to conduct research and for the contribution on technical suggestion and information sharing in terms of warehouse operations.

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INTRODUCTION

1.1 Problem Definition

Producing and distributing products in the right time and right quantity is the main focus of the manufacturing company in order to achieve a higher service level internally and to the outside customers. Competitive advantages would be earned when the order fulfillment is well-established in accordance with customer's request. In this context, speed plays a key role to adjust the service level in the production, warehousing, and distribution activities. Among factors affecting performance of company in view of the agility, material handling management is worthto be paid attention.

Material handling can bedefined as the activities concerning with movement, storage, control and protection in whole flow of materials within and/or across sites such from/to manufacturing plant, warehouse, and supply chain in order to handle material properly. In general practice, material handling tends to evoke cost as a result of spending some resources in terms of labor, capital, facility and equipment rather than saving. Therefore, handling material should be worth for the cost or expense spent by giving a value to the material itself and long term advantage to the whole process. Moreover, in industrial manufacturing company, material handling allocates some expenditure such as 25 % of all employees, 55% of all company space, 87% of production time, and 15 up to 75% of the total cost of product (Tompkins et al., 2003). Based on the definition of material handling mentioned before, it is closely related to the transporting material from/to another site. Transporting material should consider unit load concept in order to minimize time and frequency of travel which may leads to the cost reduction. To perform properly the operations, the foremost thing should be considered is selecting the appropriate material handling equipment.

In this research, we intend to highlight the problem which focuses on the material handling in the warehouse. Warehouse is a fundamental place functioned to store raw material, and finished or partly finished good and material which will be shipped out of warehouse and distributed to the distribution center or customers. The frequent operations occurred in the warehouse of finished good product, generally related to the material handling,are linked to storage and movement of product such asstoring material after being produced from production plant to be replaced to the storage pallet or stacked over the spot, moving material to be rearranged when new ongoing products are released to be stored, loading finished good product to the shipping or docking area when it will be distributed to the district warehouse or customers.

To complete the essential functions of warehouse properly, the appropriate procedure for material handling should be well determined whether it is performed by full-automated system, semi-automated system or manual. For the warehouse that applies semi-automated system for handling material, a handling device or equipment operated by human such industrial truck is needed for load, unload and transport the material. The use of appropriate material handling equipment has a major contribution to the success of warehouse operations such as achieve efficiency of space or layout and reduce cost of material handling. In fact of material handling equipment selection is need an effort, thus the consideration of all aspects should be involved thoroughly in the evaluation process before it is eventually selected. Even though utilizingmanual material handling operation is eternally much more inexpensive than controlled-machine or equipment, but however in fact, for heavy tasks, using manual equipment is unsafe for the workers or operators because of causing risk and injury in the operation.In addition, in today's industrial revolution, the issue on occupational health and safety is really concerned. In some countries, either government or private regulates manual material handling performed by human power under authority. In this condition, counting on manual material handling system is not required and selecting appropriate material handling equipment is a big deal. The complexity causing the challenge on the material handling selection process generally is triggered by the physical facility constraints, material characteristics, multiple criteria (Matson et al., 1992), uncertainty in the operation and the diversity of material handling equipment (Karande&Chakraborty, 2013).

This research intends to determine an appropriate material handling equipment which is operated in warehouse and a methodology for the selection process. This thesis is concentrated on specific warehouse equipment type, industrial truck particularly. The selection process is established by using hybrid method. The initial step is begun with acquiring the criteria of evaluation for alternatives. By referring among criteria influencing material handling equipment selection, the most suitable criteria will be chosen in view of the characteristics of material handling operations and material, and objectives depends on in which objectives we focus on, whether from the side of cost minimization, maximization of effectiveness of use, handling time reduction, or combination of those and etc. The technology, at present time, is developed rapidly and it also takes part on the development and diversity of material handling equipment. This evidently increases the number of considerable equipment as alternative and raises the problem into complex decision making. This research presents a multi-criteria and multi-objectives MHE selection problem in order to view and figure out the problem from the thorough aspects. Hence, a hybrid method is picked to incorporate the complex selection process in order to enhance the decision making for a sophisticate result.

We use a hybrid approach involving 2 different methodsthat are MCDM-based and optimization-based namely hierarchical fuzzy TOPSIS and MOMILP (Multi-Objectives Mixed Integer Linear Programming). As the initial step mentioned before in terms of MHE selection process, fuzzy AHP is used to obtain the weight of criteria for MHE evaluation and it will be inputted in fuzzy TOPSIS when the alternatives are evaluated and assessed with respect to the criteria. Fuzzy operation such as triangular fuzzy number (TFN) is utilized in both AHP and TOPSIS due to under fuzzy environment. Fuzzy environment occurs when at least the particular condition such decision maker’s opinions are conveyed under uncertain judgment or the parameters in the real case cannot be precisely predicted and measured.

Commonly, we rely on the data experience when we make evaluation toward alternatives. For instance, we speak about evaluating several alternatives accordance with the capacity. Instantly before getting through assessing the alternatives in which the alternative’s capacity is low, medium, or high, the basic evaluation will preferably go back according to the data experience because it is more able to sustain decision maker’s opinion and enhance the unanimity. To undertake data experienceas inputin determining criteria weight, entropy method is introduced and procedural determination of entropy applies for some specific conditions.By using Entropy weight-based Hierarchical Fuzzy TOPSIS, weight of alternatives are obtained.

The hybrid approach is highlighted by integrating weight of alternatives derived from Entropy weight-based Hierarchical Fuzzy TOPSIS and MOMILP dealing with multi-objectives MHE selection problem.MOMILP will be compiled according to several objective functions and constraints associating the objectives. Finally, the mathematical model is solved by using LINGO software package and final selection of MHE is undertaken.

A numerical example is generated based on the case study observedfrom a manufacturing companywhich is focused on the warehouse area.

1.2 Thesis Objectives

According to the problem definition explained in terms of MHE Selection Problem, this session brings main objectives to underline. The MHE Selection contains some issues raising the problems to solve. The questions linked to the issues are dealing with:

1. What are the critical factors or criteria influencing the MHE selection?
2. What considerationsshould be applied for selecting MHE when it is interpreted as a multi-objectives problem?
3. In order to perceive the problem in the context of multi-criteria and multi objective MHE selection, then, How to incorporate both contexts in a suitable methodology?
4. Which alternative should we select from one among industrial trucks which satisfies the best fit consideration?

By referring the issues above, the purpose of this research can be composed as follows:

1. To determine criteria and find out the importance of criteria used to select MHE for warehouse operations.
2. To provide a suitable integration model incorporating multi-criteria problem and multi objective problem.

3. To suggest the most appropriate MHE for warehouse operations.

1.3 Thesis Outline

This thesis entitled "A Hybrid Approach for Selecting Material Handling Equipment in Warehouse" consists of 8 chapters. The main idea of each chapter can be briefly explained as follows.

Chapter 1 describes about background, objectives and outlines of thesis.

Chapter 2 explains about material handling equipment which highlights the approaches to solve material handling equipment selection problem by using various methods, and discusses about principles & categories, and criteria consideration for selection.

Chapter 3 covers the knowledge about warehouse operation and the existence of warehouse for competitiveness of business process.

Chapter 4 explains the procedure of methods for MHE selection problem based on MDCM approach such as Fuzzy AHP & Fuzzy TOPSIS systematically. In addition, this chapter also introduces objective weight which derived by using entropy method and formula to integrate subjective and objective weight.

Chapter 5 explains multi objective optimization method by using AUGMECON. The developed optimization model for MHE selection problem is introduced in this session.

Chapter 6 provides a numerical example based on the case study in terms of MHE selection problem by using hybrid method.

Chapter 8provides in depth discussion and concludes the MHE selection problem throughout the thesis.

CHAPTER 2
MATERIAL HANDLING EQUIPMENT

2.1 Literature Review on Material Handling Equipment Selection

There are some studies have been established in terms of material handling equipment (MHE). Some problems focused on the single problem dealing with MHE selection for heterogeneous and homogeneous handling operation. The others focused on the mixed problem such as MHE selection and operation allocation. Both single and mixed problems are solved by using various approaches. The approach to solve MHE selection problems can be classified into four categories involving MCDM approach, expert systems, optimization approach, and hybrid approach. Here, in the following paragraph, several literatures are exposed to deal with qualitative, quantitative and integrated approach.

MCDM approach. Lashgari et al. (2012) attempted to incorporate Analytic approach for selecting MHE. In their study, fuzzy TOPSIS was applied to derived alternative priority based on the multi criteria. The combination of fuzzy AHP and ANP is used to determine the weight of sub-criteria. The combination of fuzzy ANP is applied due to consisting of dependency among the sub-criterion related to the cost criteria. Based on the depth comprehension, the weight of sub-criteria cannot be determined by using fuzzy AHP which is not able to delve into neither inner-dependency nor outer-dependency among the sub-criterion whereas ANP is fully effective to deal with that.

The integration approach of MCDM such as fuzzy ANP and fuzzy TOPSIS is also used to solve the material handling selection problem. A study established by Onut et al. (2009) applied it for selecting material handling equipment in the steel construction industry. Fuzzy ANP is performed to determine the criteria weight and use the weight to assess the alternative which is established by using fuzzy TOPSIS. Similarly, fuzzy ANP was also proposed to MHE selection problem and integrated to fuzzy PROMETHE (Tuzkaya et al., 2010). The importance weight of evaluation criteria affecting MHE selection are derived by fuzzy ANP. The final rank of alternatives is constructed based on the fuzzy PROMETHE procedures.

Karande & Chakraboty (2013) used weighted utility additive theory (WUTA) for material handling equipment selection. The selection is based on the multi-criteria. AHP is performed to solve the material handling selection problem (Chakraboty & Banik, 2006).

Another method of MCDM applied for material handling equipment selection, that it is simple additive weight (SAW). Sagar et al. (2013) adopted SAW to select an appropriate material handling equipment. The expert's judgment is translated into triangular fuzzy information. To see the final rank, the assessment from all experts as an average fuzzy score is defuzzified as a crisp score.

An integrated fuzzy AHP-fuzzy TOPSIS is adopted by Chamzini & Shariati (2013) for material handling selection problem. The problem deals with selection of the best material handling equipment for the case study in surface mine. In order to consider the criteria evaluation, fuzzy AHP is used to obtain the weight of criteria and then integrated to the fuzzy TOPSIS to tackle the final selection.

Expert systems. in this approach, a knowledge based-systems and database management techniques is used to help the decision maker in selecting MHE by using some required attributes. Several experts systems have been developed and adopted to assist the MHE selection problem such as EMHES (Attia et al, 1992), MAHSES (Kim & Eom, 1997) and MATHES (Fisher et al., 1988). Vijarayam (2006), in the review of material handling technology and experts system for MHE selection, summarized briefly software and expert systems used to help selecting MHE (shown in table 2.1).

Kulak et al. (2004), in the paper entitled "multi-attribute material handling equipment selection using information axiom", developed a decision support system applying fuzzy MADM. The evaluation and selection of material handling equipment are made by using fuzzy Information axiom approach.

Rubinovitz & Karni (1994) introduced expert system approaches to the selection of materials handling and transfer equipment. Expert system is also proposed to conveyor selection (Fonseca et al., 2004). A notable expert system package namely MATHES (Material Handling Equipment Selection), is introduced by Fisher et al. (1988) for material handling equipment selection.

Table 2.1. Software package & expert systems in MHE application

No	Software package of experts systems	Year created
1	SEMH (Selection of Equipment for Material Handling)	1984
2	Prototype expert system for industrial truck type selection	1987
3	MATHES (Material Handling Equipment Selection Expert System)	1988
4	MAHDE	1988
5	MHES (Material Handling Equipment Selection)	1989
6	MATHES II (Material Handling Equipment Selection Expert System II)	1990
7	EXCITE (Expert Consultant for in Plant Transportation Equipment)	1990
8	EMHES (Expert System for Material Handling Equipment Selection)	1992
9	ICMESE (Intelligent Consultant System for Material Handling Equipment)	1996
10	MAHSES (Material Handling Selection Expert System)	1997

Optimization approach. Burt (2008) in her thesis related to the material handling equipment selection developed an optimization model for material handling equipment selection in surface mining. A MILP was formulated by considering several conditions such as single and multi–period mining schedule, single and multi-location and utilized cost based equipment selection.

Zu et al. (2013) presented a research regarding the design of large ship material handling system. The analysis of material handling system for large ship and selection of the material handling equipment were discussed further. Selection of the material handling equipment was made based on the optimization model in in view of the two supply ways (shore-to-ship supply and ship-to-ship supply). The optimization model was constructed as multi-objective and multi-constraint optimization problem.

A fuzzy goal programming model was applied to solve the machine tool selection and operation allocation problems in a flexible manufacturing system (Tiwari et al., 2002). The objective functions are addressed to minimizing total cost of machining operation, material handling and set up. Genetic algorithm was also applied to get through the procedure of optimization from fuzzy goal programming in order to obtain the final optimal solution.

Paulo et al. (2002) also come up with machine tool selection and operation allocation problems in a flexible manufacturing system by using optimization model. The objective is to select an optimal group of materials-handling equipment to be assigned to a cell.

Hybrid approach. Braglia et al. (2001) proposed a hybrid approach by using AHP and integer linear programming to deal with material handling device selection in cellular manufacturing particularly. The problem involves several cells in manufacturing line. The integration is emerged to incorporate the investment decision. The overall weight of each alternative derived from AHP is applied to the integer linear programming. It aims to achieve the maximum goodness of the material handling device selection. The result suggested that each cell is be served by different material handling device which is most appropriate one.

Integration of expert systems and MCDM approach was developed by Chan et al., (2001). Expert systems packaged called MHESA (material handling equipment selection advisor) was built from three modules that they are database systems for material handling equipment, a knowledge-based expert system for assisting material handling equipment selection, and the third module performs the selection process of material handling equipment by using AHP method which represents the integration of the expert system and MCDM approach.

2.2 Material Handling Equipment: Principles and Categories

Principles of material handling design can be addressed to the ten principles of material handling compiled by College Industry Council on Material Handling Education (CIS-MHE) collaborating with the Material Handling Institute (MHI). According to the observation conducted for many years which engages many practitioners and students in contributing the experience and knowledge, Ten Principles of Material Handling can be defined as follows:

1) **Planning Principle**

   All material handlings should be planned based on the holistically determination and the foremost thing to consider such as the needs, performance objectives, and functional specification of the proposed method should be defined at initiation.

2) **Standardization Principle**

   Material handling method, equipment, controls and software should meet the standardization by taking into account the target limits of overall performance objectives and without neglecting the needed flexibility, modularity, and throughput.

3) **Work Principle**

   Material handling work (which is derived from multiplication of material flow and distance moved) should achieve the minimum value but still worth for the advantages posed relating to the productivity and service level required for the operation.

4) **Ergonomic Principle**

   Interaction between operators/workers/human and either material handling task or equipment should conform to ergonomic aspect in order to produce safety and effectiveness in operation.

5) **Unit Load Principle**

   Unit loads should be sized and configured appropriately in a sophisticated manner so that the material flow and inventory objective at each level of supply chain can be achieved.

6) **Space Utilization Principle**

   Material Handling tasks and equipment should be designed by considering the available space and path.

7) **System Principle**

Material movement and storage should be integrated to the a coordinated form, operational system assigning the receiving, inspection, storage, production, assembly, packaging, unitizing, order selection, shipping, and transportation, and the handling of returns.

8) **Automation Principle**

Aiming to improve operational efficiency, increase responsiveness, improve consistency and predictability, decrease operating costs, and to eliminate repetitive or potentially unsafe manual labor, by expecting the purposes, it is proper to select the automated material handling systems.

9) **Environmental Principle**

Alternative equipment & MHS design and selection should be made by taking into account influential criteria such as environmental impact and energy consumption.

10) **Life Cycle Cost Principle**

Before executing the alternative and making a final decision, the cost resulting in generating material handling equipment and systems should be estimated with a thorough economic analysis. The consideration might leads to the cost which is feasible for the life cycle.

Characteristics of material do seem affect the handling systems and equipment or tool used. Several characteristics such as size (width, depth, height), weight (weight per item or per unit volume), shape (round, square, long rectangular, irregular), slippery, fragile, sticky, explosive, and frozen are influential for the material handling systems. The characteristic of material can be categorized in table 2.

Table 2.2. Material category

Material Category	Physical State		
	Solid	Liquid	Gas
Individual units	Part, subassembly	-	-
Containerized items	Carton, bag, tote, box, pallet, bin	Barrel	Cylinder
Bulk materials	Sand, cement, coal, granular products	Chemicals liquid, solvents, gasoline	Oxygen, nitrogen, carbon dioxide

There are so many equipment that can be used to material handling, but there are some equipment that should be pointed out as major and widely used equipment in manufacturer or factory. That material handling equipment can be classified into 5 main categories (Chu et al, 1995):

1) **Transport Equipment**

In this category, equipment is used to move material from one location to another such move the material between workplaces, a loading dock and a storage area. Several major equipment which can be used as transport equipment are:

a. Conveyors. Kinds of conveyors commonly used in manufacturing industry within the recent years are such:
   - Chute conveyor
   - Wheel conveyor
   - Roller conveyor
   - Chain conveyor
   - Slat conveyor
   - Flat belt conveyor
   - Magnetic belt conveyor
   - Toughed belt conveyor
   - Bucket conveyor
   - Vibrating conveyor
   - Pneumatic conveyor
   - Vertical conveyor
   - Cart-on-track conveyor
   - Two conveyor
   - Trolley conveyor
   - Power and free conveyor
   - Monorail conveyor
   - Sortation conveyor
   - Screw conveyor

b. Cranes. Unlike conveyor, cranes are developed in few variety.
   - Jib crane

– Bridge crane
– Gantry crane
– Stacker crane

c. Industrial truck

– Hand truck
– Pallet truck
– Pallet jack
– Walkie stacker
– Platform truck
– Counterbalanced lift truck
– Personnel and burden carrier
– Narrow-aisle reach truck
– Turret truck
– Order picker
– Slide loader
– Tractor trailer
– Narrow-aisle straddle truck
– Automated guided vehicle

For transport equipment, there are some different characteristics on functional operation among conveyor, crane and industrial truck. The different functional can be seen from path of the equipment move, required area to enable for movement, move frequency, and adjacent move. It can be summarized in table 3.

Table 2.3. Characteristics of transport equipment

Path	Fixed			Variable		
Area	Restricted			Restricted		Unrestricted
Frequency	High	Low		High	Low	-
Adjacent	-	YES	NO	-	-	-
Transport equipment	Conveyor	Conveyor	Industrial truck & Crane	Industrial truck	Crane	Industrial truck

Summary on the table above can be described as follows:

- Path

Fixed : move between two specific points

Variable : move between a large variety of points

- Area

Restricted : move restricted to a limited area

Unrestricted : move to unlimited area

- Move frequency

  Low : low number of moves per period or intermittent moves

  High : high number of moves per period

- Adjacent move

  Yes : move is between adjacent activities

  No : move is between activities that are not adjacent

2) Positioning Equipment

The equipment included in this category are used to handle the material at a single location, for example, use to feed or manipulate materials so that it can be settled in the correct position for subsequent handling, machining, transport or storage. By contrast, Transport equipment is not able to be operated across workplace like transport equipment instead it is only used for handling at a single workplace. Several equipment used to positioning material are:

- Lift/tilt/turn table
- Dock leveler
- Ball transfer table
- Rotary index table
- Part feeder
- Air film device
- Hoist
- Balancer
- Manipulator
- Industrial robot

3) Unit Load Formation Equipment

This equipment has a function for restricting materials in order to maintain the integrity when handle a single load during transporting and storing. If materials can restrain by itself such as a single part or interlocking parts, then it can be formed into a unit load without equipment. These are commonly used unit-load-formation equipment:

- Pallets
- Skids
- Slipsheets
- Tote pans
- Pallet/skid boxes
- Crates
- Intermodal containers
- Strapping/tape/glue
- Shrink-wrap/stretch-wrap
- Palletizer

- Bins/basket/racks
- Cartons
- Bags
- Bulk load containers

4) Storage Equipment

In general, storage equipment is functioned as a holder or buffer of material for long duration of time. Some storage equipment usually include the transport of materials for example the S/R machines of an S.RS, or storage carousels. The material which is stored into stacked lock and placed directly on the floor doesn’t need storage equipment. Storage equipment vary according to the shape and type of material stored, some of them are:

- Selective pallets rack
- Drive-in rack
- Drive-through rack
- Push-back rack
- Flow-through rack
- Sliding rack
- Cantilever rack
- Stacking frame
- Bin shelving
- Storage carousel
- Vertical lift module
- A-frame
- Storage drawers
- Automatic storage/ retrieval system

5) Identification and Control Equipment

This equipment has two main functions which are, to collect the information and communicate information controlling the coordination of the materials flow within a facility and between a facility and its suppliers and customers. The identification and control of material can be performed with another way that is without specialized equipment. Some of this equipment are such:

- Bar code
- Radio frequency identification tags
- Voice recognition
- Magnetic stripes
- Machine vision
- Portable data terminals

2.3 MHE Selection: Problem overview & Criteria

Alternatives selection of MHE can consider the one satisfying the requirements. But, evaluating the one satisfying the requirement would take the time and effort when the requirements are broken down into many criteria and generating the alternatives in high number will increase the complexity. Depend on which level of MHE is focused related to the MHE categories, types, and models, MHES can be classified into 3 levels:

1. High level

   MHES problem is focused on seeking a suitable MHE among the categories, e.g., conveyors, cranes, industrial trucks, positioning equipment etc.
2. Intermediate level

   MHES problem is focused on seeking a suitable type of MHE within a category, e.g., selecting the best alternatives of among conveyors category (chute or wheel or roller).
3. Low level

   MHES problem is focused on seeking a suitable model of MHE within a type, e.g., selecting the best alternatives of among hand pallet truck types in terms of dimension (Model PTH 50 27-48 or PTH 50 20-48 or PTH 50 20-36).

Selecting MHE as a low level problem would be tougher because it can bring the result in too many possible alternatives. Capturing MHES problem from a high level does not narrow the number of possible alternatives enough. Whereas selecting MHE from intermediate level reduces the possible alternatives to be chosen from 15-50 possible types of MHE.

The process of MHE selection can be decomposed into two stages (see figure 1):

1. Determine Technical Feasibility

   Based on the technological perspective, consider MHE types which can satisfy the material flow requirement. For example, a pallet jack is not technically feasible for stacking pallets onto storage racks.
2. Determine Economic Feasibility

When the considerations from technical feasible equipment types have been determined, one is the most cost effective given the material handling requirements can be chosen among those. For example, while both a pallet jack and pallet truck are technically feasible for long distance moves, from cost effective objective, pallet truck is better choice because it can travel faster due the operator's ability to ride on truck.

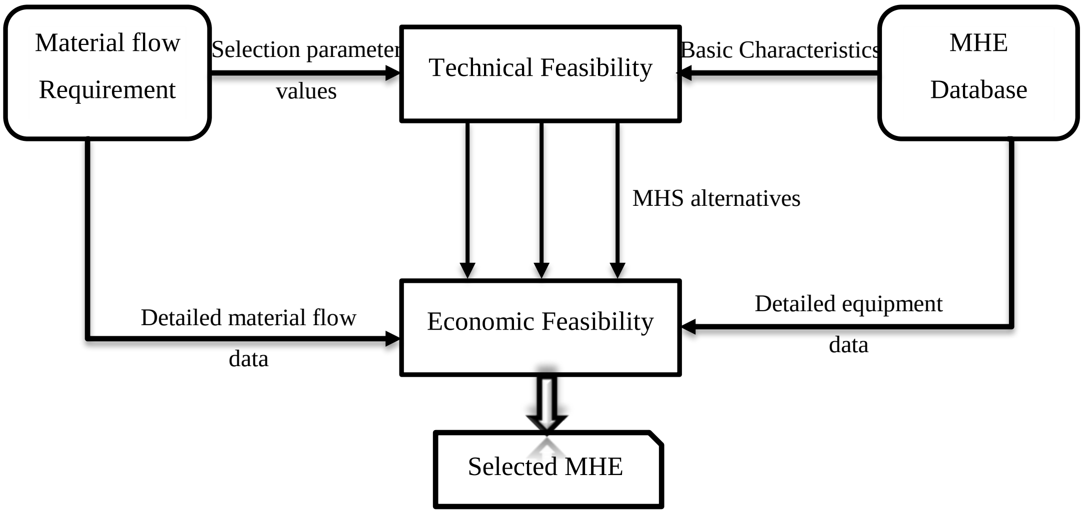

Figure 2.1. MHE selection mechanism

The evaluation criteria for MHE selection can vary depend on the particular factors such as operation types, equipment category, etc. In the following paragraphs, the consideration of MHE selection is explained according to the literature and study.

From a case study, loading and hauling system in surface mines is the main issue. The most suitable equipment performing loading and hauling operations is attempted to find out. MHE selection problem particularly for loading equipment is evaluated according to some criteria as follows (Lasghari *et al*., 2012):

1. Capital cost
2. Operating cost (maintenance cost, overhaul cost, fuel/power cost, lubrication cost, tire & wear part)
3. Operational parameters. This factor includes several break-down criteria:

- Daily production rate
- Operator skill

– Assay and blending
– Rolling resistance
– Bench height
– Inflation factor
– Ground condition
– Moisture
– Environment
– Breaking size of blasting
– Technical parameters
– Fill factor
– Matching with truck
– Maintenance
– Utilization
– Flexibility
– Mobility
– Availability
– Continues working
– Working stability
– Working space
– Time cycle
– Useful life
– Automation

The taxonomy and sub-criteria was developed which is applicable for general material handling equipment selection in view of 4 categories of MHE including conveying systems, industrial trucks, cranes and hoists, and auxiliary equipment. The taxonomy and sub-criteria can be summarized as 3 major factors that are material, move, and method (Chakraborty & Banik, 2006):

1. Material type:
   a. Unit – single number
   b. Bulk – multiple numbers
   c. Fluid – any type of liquid or gas
2. Material characteristics:
   a. Shape and size – regular, irregular or variable
   b. Material volume – less than 0.0035 cum, between 0.002 and 0.0035 cum, or more than 0.002 cum
   c. Nature – fragile, sturdy or bulky
3. Material quantity:
   a. Low – less than 2275 kg
   b. Medium – between 2275 and 7500 kg
   c. High – more than 7500 kg

4. Material source and destination:

   a. Distance – distance to be travelled by the equipment is less than 30 m, between 30 to 90 m, or above 90 m
   b. Level – floor level, working level, or over height in horizontal, vertical and inclined directions
   c. Path – fixed direction, variable direction or curved path

5. Move characteristics:

   a. Speed – uniform, irregular or variable
   b. Frequency – movement rate per unit time in a specified period – fixed, continuous or intermittent
   c. Course – fixed point to fixed point, fixed point to variable point, or variable point to variable point

6. Move type:

   a. Stacking of material to store
   b. Transferring of material from one place to other
   c. Positioning such as elevating or lowering within specified location or direction

7. Logistics:

   a. Load handled/hour – uniform, variable or combination
   b. Location – indoor, outdoor or mixed
   c. Area covered – point to point, confined or variable

8. Control:

   a. Automatic
   b. Manual
   c. Self

9. Acquisition cost: Cost of the equipment spending for installation and commissioning charges is

   a. Low
   b. Medium
   c. High

10. Handling cost:

   a. Uniform
   b. Variable
   c. Irregular

11. Facility:
    a. Clear height – less than 3 m, between 3 m and 15 m, or more than 15 m
    b. Aisle – applicable or not applicable
    c. Power requirement – whether external power is required

In the cellular manufacturing systems, material handling equipment was selected from the evaluation according to 3 major categories that are cost category, benefit category, and compatibility category (Braglia et al., 2001). MHE selection is dealing with multi-alternatives and multi-cells. Evaluation criteria involving 3 major categories can be structured into detail:

a. Cost category

1. Purchase cost:
   - MHE cost
   - Installation cost
2. Operation cost:
   - Labor cost
   - Energy cost
3. Logistic support cost:
   - User training
   - Dismantling
   - Maintenance:
     - Spare cost
     - Spare part holding cost
     - Repair labor cost
     - Maintenance training

b. Benefit Category

1. Purchase benefits:
   - Guaranty
   - Payment modality
2. Operation
   - Operative flexibility
   - Reliability
   - Safety
   - User friendliness
   - Space
3. Strategic flexibility
4. Performances:
   - Velocity
   - Load
   - Accuracy
   - Service area

c. Compatibility Category

1. Workplace:
   - Size
   - Weight
2. Equipment:
   - Displacement velocity

– Space
– Ancillary equipment
– Structural adjustment

Momani & Ahmed (2011) defined criteria and sub-criteria of MHE evaluation by adopting and modified evaluation criteria of MHE from the different past studies which are conducted by Kulak (2005) and Chakraborty & Banik (2006). The criteria were developed to incorporate MHE for carrying the material from packaging department to the main storage. The developed criteria listed below are divided into 3 categories which are material, move, method.

1. Materials
   a. Characteristics of material:
   – Weight
   – Shape
   – Volume
   b. Type of material:
   – Fluid
   – Bulk
   – Unit
2. Move
   a. Source & Destination:
   – Distance
   – Path
   – Level
   b. Characteristics of movement:
   – Speed
   – Frequency
   c. Type of movement
3. Method
   a. Facility restrictions:
   – Height
   – Aisles
   – Area
   b. Control method
   c. Safety
   d. Fixed cost
   e. Variable cost
   f. Maintainability
   g. Variability

A study has been conducted in order to evaluate the impact of implementation changes in material handling management at production department. The evaluation procedure is held based on the evaluation criteria and sub criteria which indicate the significant change in implementation. The capable internal customers such as leaders, supervisors, forklift drivers and warehouse operators are included in deriving the criteria and sub-criteria. Although the criteria and sub criteria are determined not as direct consideration for selecting MHE, but the evaluation criteria represent the forthcoming yield obtained over the selected MHE after being implemented. Vieira et al., (2011) summarized the success factors of evolution of MHE implementation by 4 criteria shown as follows.

1. Cost:

   Monetary value exists to support the operation maintenance such as expenditures of the MHE used in terms of periodic maintenance. This criterion involves:

   a. Mechanical shutdowns
   b. Electrical shutdowns
   c. Corrective painting

2. Safety in Service:

   Identifies MHE operator's conduct on new handling and internal transport way.

   a. Safety in handling
   b. Tooling storage
   c. Efficient routing

3. Service Reliability:

   Identifies manufacturing satisfaction level in terms of reliability

   a. Operator's autonomy
   b. Operator's performance and availability

4. Agility:

   Identifies the time spent due to the running MHE with additional tool exchange handling (discounting the times associated with the machine, such as loose and/or fix arrays or tools).

   a. Setup agility
   b. Material handling quickness
   c. Tooling handling quickness

CHAPTER 3

WAREHOUSE OPERATIONS

3.1 The Essential Existence of Warehouse

In fact, building a warehouse consumes a lot of resources such as capital, labor, and time, which, those are costly. But, another side, warehouse is operated in view of holistic purpose for long term consideration. In this perspective, the idea is to sustain the success of business process because warehouse evidently provides useful services. To be reasonable with the warehouse existence in terms of giving positive values, here the fundamental functions of warehouse can be coherently explained for that:

1. **To consolidate product**

   Establishing product consolidation properly will reduce transportation cost and provide good customer service. Whenever the product is distributed, it will cause a fixed cost. The amount will be high especially when it is transported by using carrier such as ship, plane, and train. This affects reaction to assign the carrier with maximum load so that it can pay off the fixed cost. Consequently, a distributor may consolidate shipments from vendors into large shipments for downstream customers. Similarly, the consolidated shipments will enable to ease in receiving downstream. Trucks which are going to ship the order usually take the assignment according to the available number of dock doors and so the drivers don't have to wait. The final impact raises the savings for whole parties.

   Consider an example, Home depot as a major storage point generally accommodates products from many vendors. The most common problematic condition as a given example is when the number of receiving docks is insufficient which contain only 3 doors. A store receives shipments at least weekly and so for large quantity of products, it is not possible to be loaded by the truck. In this condition, shipment from a vendor to a store must be done by less-then-truck-load (LTL) carrier. It will increase transportation cost due to higher shipment frequency. But while most stores cannot fill a truck from a vendor, all the home depots can store in aggregate certainly, and several times over. The saving cost of transportation can be one of the reasons to justify shipping full truck loads from vendors to a few consolidation centers, which then ship full truck loads to other stores.

2. To realize economies of scale in manufacturing or purchasing

Vendor may give a price break to bulk purchases and the saving may offset the expense of storing the product. Similarly, in the manufacturing, economics of scale does coherent so. To realize economic achievement, producing in a large batch size is often relied to pay off high setup costs, so that the excess products need to be stored.

3. To provide value-added processing

At recent time, warehouse is compelled to contribute for the continuity over the whole manufacturing process and likened as light assembly which gives value-added processing. The contribution of warehouse can be seen explicitly in a manufacturing company performing product differentiation. In this environment, the manufacturer produces a final product which is assembled from many components according to customers-based configuration. Some components are shipped to a certain destination to be assembled, as they pass through a warehouse. This enables the manufacturer to react responsively toward the change of product type by customer. It influence the safety stock where it can be lower and ultimately inventory levels can be lower because the circulation of each item is rapid.

4. To reduce response time

In the country where the infrastructure particularly for transportation facilities is undeveloped or poorly developed, the manufacturers may confront a problem in distributing product inside or outside the region. The most common problem to face is poor response time. For example, shipping sub-assemblies across countries to a manufacturer. Based on the common procedure, across country shipment will go through several stages and it will be unloaded at a busy port, pass through customs, then transport by rail or something else, and subsequently by truck. This makes the shipping time longer. In fact, in each stage the process will take times longer than it schedule due to delay by congestion or slow process of bureaucracy, bad weather, road condition and so on. Thus, it affects lead time becoming so long and variable. Hence, warehouse can be one of the ways to tackle this condition. By opening a distribution warehouse in region nearby, this problem can be avoid and be minimized in order to achieve high response time and short lead time in distributing product because it provides a storage point closer to customer for availability of product whenever it is demanded.

3.2 Warehouse Operations

Warehouse is a commercial building used by manufacturers, importers and exporters, wholesalers etc. for storage of good including raw materials, packing materials, components, subassemblies, and finished good product. Good moves in and out of warehouse through particular operations until ready to be shipped. Warehouse operations can go through several stages and the number of operations may vary in each warehouse depends on warehouse operation assessment strategy. Efficient warehouse operations can ensure that a company ships and receives vital stock in time for replenishment on store shelves or in manufacturing facilities (Johnson, 2014). Efficient warehouse operations are not unintentionally conducted, but instead it happens because of adherence to initiatives of a series of best practices. The way of organizing operations including all planning and control procedures used to run the system literally influences the warehouse characteristics. In general, good takes place in a warehouse through the following processes (see figure 2):

a) Inbound processes
    1. Receiving
    2. Put-away
b) Outbound processes
    1. Processing customer orders
    2. Order-picking
    3. Checking
    4. Packing
    5. Shipping

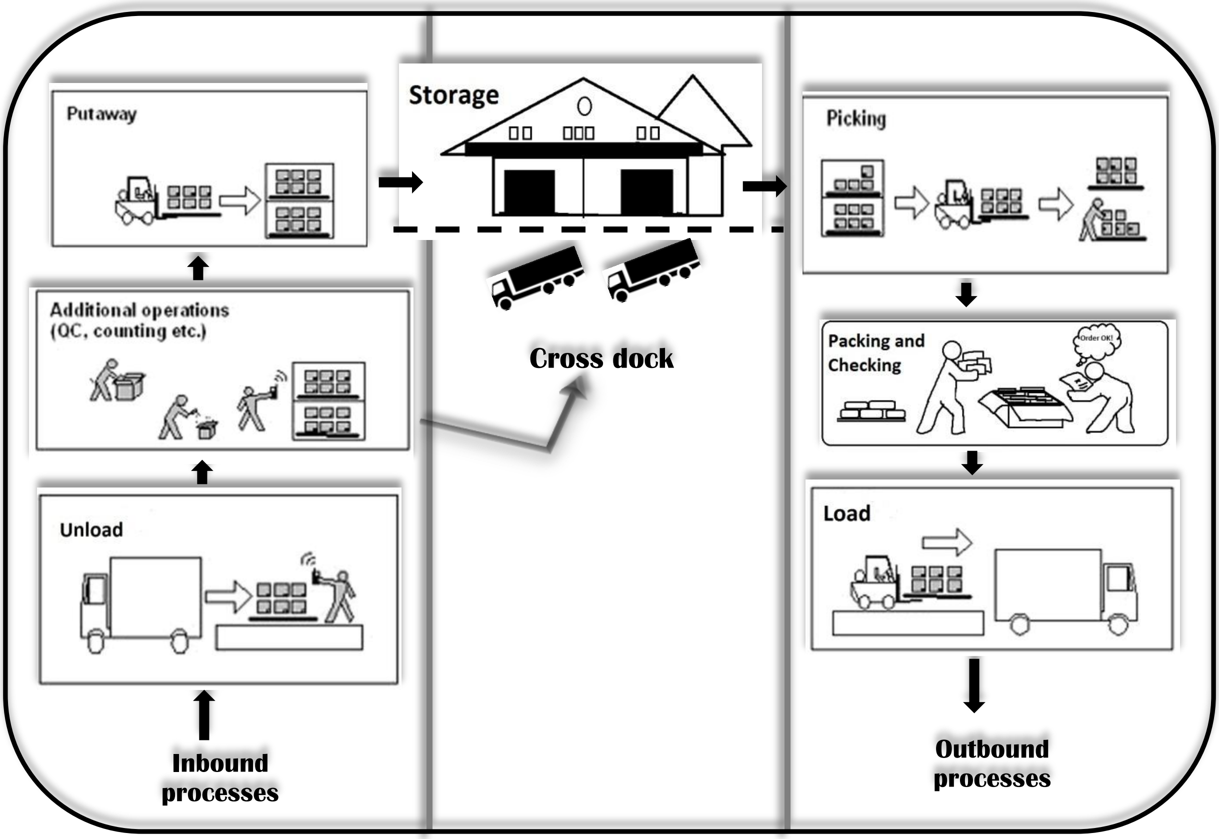

Figure 3.1. Warehouse operations

Receiving

Receiving can be initially done through an advance notification when the goods arrive. This guides the warehouse to arrange the receipt and unloading schedule to certain direction efficiently with other processes within the warehouse. Receiving accounts for about 10% of operating costs in a typical distribution center (Frazelle, 2002). When the good arrives, the following tasks will be performed in order to receive it:

- Unload and stage for put away.
- Good commonly will be scanned to register its arrival so that the good’s ID can be known and available both for payment dispatched and order fulfillment according to the customer demand.
- Inspect good and note for any exceptions such as damage, incorrect counts, wrong description and etc.

- Good typically arrives in large unit such as pallets and it is likely placed in mixed pallets. Therefore good should be re-palletized into separate cartons to avoid incorrect put away and when its carton is loose.

Put-away

Before good can be put away, an appropriate storage location must be determined. This is very essential because of related to the time and cost spending for exploration. When good is put away, we should track and record its storage location to ease seeking the product then. The information recorded yields a pick-list which is useful to guide the order-pickers efficiently in retrieving goods for customers. Put-away typically accounts for about 15% of warehouse operating expenses (Frazelle, 2002).

Process Customer Orders

To decide the customer order whether it is approved or not, the order from certain good must be checked to verify regarding the inventory availability so that fulfillment can be made certainly. Then, order pick-list should be created to guide the order –picking and other information should be documented to control the order picking and shipping and its schedule. The tasks in processing customer order are generally supported by using software controlled for warehouse management systems, a full-package system which organizes and monitors the entire operations of warehouse.

Order-picking

Order-picking is the most consumptive operations among other warehouse operations. It typically accounts for about 55% of warehouse operating costs (Frazelle, 2002). The tasks included in order-picking can be divided into 4 major tasks as shown in table 2.

According to the order-picking tasks above, it is evident that traveling takes the greatest part of the expense of order-picking. It is reasonable to reduce travel time within order-picking operations in view of reducing waste time and improving productivity as if it spends the highest consumption in process among other tasks.

Table 3.1 Activities involved in order-picking

Tasks	% Order-picking time
Traveling	55%
Searching	15%
Extracting	10%
Paperwork and other activities	20%

One manufacturer to another manufacturer may apply different strategy for order-picking operation in warehouse. In real operational, there are some order-picking strategies or systems which are familiar to apply. According to the order-picking systems classified by De Koster (2004), order-picking systems can be distinguished into 2 main categories which are humans and automated machines, the details can be explained as follows:

a. Employing humans

1. **Picker-to-parts**. This system performs the order picker to walk or drive along the aisle for picking items. There are two types in this system which can be categorized as:
   a. Low-level order picking systems, the order picker will take requested goods from storage area while traveling along the storage aisles.
   b. High-level order picking systems or a man-abroad order-picking systems. This system typically stores goods in high storage rack system. Order picker uses lifting truck or crane while traveling and picking the listed order.

Other picker-to-parts systems can be distinguished into several types such as follows:

a. Picking by article (batch picking) or Picking by order (discrete picking), this performs order-picking for multi customer orders as a batch. This system can be done by using 2 ways:
- Sort while-pick, order picker will pick multiple orders through immediate sorting according to pick-list.
- Pick-and-sort, order picker will sort multiple orders after the pick process has finished.

b. Zoning, storage area is separated based on the storage equipment used (such as item A is stored in pallet storage area) and it is split in multiple parts. Each storage area will be operated by different order pickers. for further detail, zoning system can be classified into 2 types depending on whether orders picked in a zone are passed to other zones for completion or picked in parallel:

- Progressive zoning
- Synchronized zoning

The term wave picking is used if orders for a certain destination (for example, departure at a fixed time with a certain carrier) are scheduled concurrently to be picked in multiple warehouse areas. Sometimes, in fact, wave picking can be performed by combining batch picking system. The batch size is determined based on the required time to pick the whole batch.

2. Part-to-Picker systems include automated storage and retrieval systems (AS/RS). Retrieval process is commonly conducted by using aisle-bound cranes so that it is possible to retrieve more than one unit loads. The small unit loads are also able to be handled by using small capacity MHE such as pallets or bins, in this case which is called a miniload systems. Then, items loaded will be brought to a pick position (i.e a depot) and picked as many as required number of order by order-picker, after which the remaining loads will be stored again. This type of system is also known as a unit-load or end-of-aisle order-picking system. The large unit loads can be tackled by using automated crane (S/R machine) which is able to work under different operating modes:

- Single-command cycles. This mode enables a load to move concurrently from the depot to a rack location or from a rack location to the depot.
- Dual-command cycles. This mode works by moving a load from the depot to the rack location and next another load is retrieved from the rack.
- Multiple-command cycles. This mode has a S/R machine which consist more than one shuttle and can pick up and drop off several loads in one cycle.

In addition, other systems of part-to-picker can be operated by using *modular vertical lift modules (VLM), or carousels* that also offer unit loads to the order picker, who will pick the items based on the required number.

3. **Put systems (or order distribution systems)** is conducted through 2 procedures which are retrieval and distribution process. Put-system is initialized with retrieving items where it can be done through order-picking system in a parts-to-picker or picker-to-part manner. Then, order-picker will be ready to pick the pre-picked items served initially by the carrier (from a bin) and distribute them over customer orders ('put' them into a package correspond the customer label).

b. Employing machines

Order-picking is completed under machines control. The technology adopted engages automated-picking and robotized-picking systems used in case for handling valuable, small and delicate goods.

Checking and Packing

When the order fulfillment should be made, requested product should be prepared earlier for packing to avoid unpunctual fulfillment schedule. In order fulfillment for multi-product and large number, it definitely needs extra inspection or checking in terms of quantity, specification, etc. because each requested product must be checked one by one within the packing process. All findings in checking process regarding unsuitable items should be documented and reported, where it is usually integrated to the WMS for sharing and handling warehouse information and data. The accuracy of packing operator is examined in need. Inappropriate order to customer will affect customer's satisfaction and trust in negative appreciation. Therefore, in this stage of warehouse operations, checking accuracy during packing process is a key measure of service to the customer.

In general, products are packed into shipping cartons, and especially for fragile products, the air space in cartons is filled with a packing media for extra protection, then sealed. Cartons are also stamped, labeled, and otherwise marked as needed for shipping confirmation which shows that the customer order specifications is under declaration. Hence, once again, not only to checking the order per item, but checking process is also required for the package.

Shipping

Packed products are loaded to the vehicle to be shipped. Products must be loaded into appropriate vehicle according to the vehicle assigned in where it should transport to which customer. It is usually considered shipping's responsibility to ensure that all shipments are picked up the day they are ready to ship and that all shipping paperwork is routed to the correct departments at the end of each shipping day. Therefore, vehicle should be scanned to register its departure from the warehouse. One of the important things during loading when one vehicle is assigned to multi-customers order is manage the shipped order in efficient pattern, in which shipped order should be loaded in first row and respectively into the container. It should be paid attention because in fact, loading and unloading process spend long duration. Hence, in view of time minimization, shipped order can be loaded according to LIFO system which means taking last shipped order in first order, for example, customer order with the longest distance or last stop will be loaded in first order into container, by contrast, customer order with the shortest distance or first stop will be loaded in latest order.

CHAPTER 4

MULTI-CRITERIA DECISION MAKING APPROACH

3.1 Determine Weight of Criteria

3.1.1 Subjective Weight: Fuzzy AHP

The fuzzy theory was introduced by Zadeh (1965) as an extension of the classical notion of set. Among the various shapes of fuzzy number, triangular fuzzy number (TFN) is the most popular one. TFN is a fuzzy number represented by three points which is shown in figure 4.1. A fuzzy number $\tilde{A}$ = (*l*, *m*, *u*) on $\mathbb{R}$ will be a TNF if its membership function $\boldsymbol{\mu_{\tilde{A}(x)}}$ **:** $\mathbb{R} \rightarrow [0,1]$ is equal to the following:

$$\mu_{\tilde{A}}(x)=\begin{cases} 0 & for\, x < l\, ;\, x > u \\ \frac{x-l}{m-l} & for\, l \leq x \leq m \\ \frac{u-x}{u-m} & for\, m \leq x \leq u \end{cases}$$

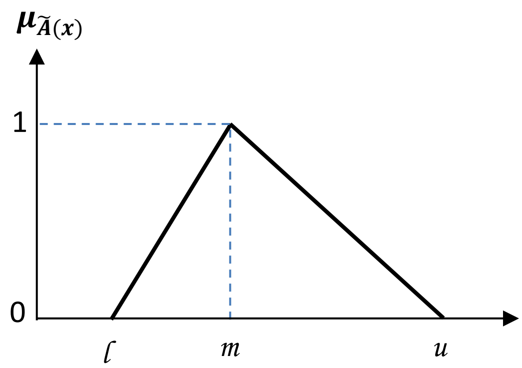

Figure 4.1. Triangular fuzzy number

where *l*, *m*, *u* are the real number which respectively represent lower, middle, and upper bound.

AHP, firstly introduced by Saaty (1980), is one of decision making techniques which applies pair-wise comparison matrix to measure the relative importance of criteria. Since vagueness and uncertainty exist in DMs' opinion, the importance rating cannot be used to represent imprecise judgment. For improving the DMs' opinion in fuzzy environment, Laarhoven and Pedrycz (1983) proposed Fuzzy AHP by adopting triangular fuzzy number which refers to fuzzy set theory introduced by Zadeh. Their study also enlightened the comparison result of applying classical importance rating and fuzzy triangular importance rating to AHP. By referring to fuzzy logic, triangular fuzzy number (TNF) (Kutlu& Ekmekçioglu, 2012; Sun, 2010; Hsu et al., 2010, Pan, 2008) and trapezoidal fuzzy number (Cunbin & Peng, 2012; Tian et al., 2012;Tolga & Kahraman, 2008; Buckley, 1985) are most often used to develop importance rating of classical AHP and incorporate decision making process under vagueness and uncertainty. Chang (1996) proposed a new approach to perform fuzzification in AHP by using triangular fuzzy number and in this study, the analysis extent of synthetic value was used.

In this study, Fuzzy AHP is used to determine subjective weight for evaluation criteria through pair-wise comparison. The procedures can be briefly explained by the following steps:

1. Define the problem. Problem should be generalized clearly through defining what the main problem with respect to the objective, identifying criteria (i= 1,2,…,n), sub-criteria (l=1,2,…,L), and alternatives (m=1,2,…M) related to the problem. The decision maker should be determined whether it is single or multi decision maker. On the other hand, set the number of k-decision maker (k=1,2,.., K).

2. Construct problem into hierarchy. This step defines the problem into level of hierarchical structure including in order respectively objective, criteria, sub-criteria, and alternatives.

3. For each k-decision maker, construct pair wise comparison matrix for criteria and sub-criteria by using Saaty's importance scale 1-9 which is shown in table 1.

Table 4.1. Saaty's importance scales

Importance Intensity	**Definition**
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate

4. Perform consistency test for each pair wise comparison matrix. Saaty (1980) suggested the maximal eigenvalue (λ_{max}) used to evaluate the effectiveness of measurements. Let V denotes an n-dimensional column vector indexing the sum

of the weight values for the importance scale of criteria and it can be determined by using formula bellow:

$$V= [v_i]_{nx1} = A.W^T = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} [w_1, w_2, \ldots, w_n]= \begin{bmatrix} V_1 \\ V_2 \\ \cdots \\ V_3 \end{bmatrix}, \quad (4.1)$$

i = 1,2,…,n

Finally, λ_{max} can be determined by dropping those values into formula below:

$$\lambda_{max} = \frac{\sum_{i=1}^{n} \frac{V_i}{W_i}}{n} \quad , i = 1,2,\ldots,n \quad (4.2)$$

To check the consistency between pairwise comparison matrices, the consistency index (CI) and consistency ratio (CR) are estimated using the equations:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (4.3)$$

$$CR = \frac{CI}{RI} \leq 0.1 \quad (4.4)$$

where RI is a random index with a value obtained from Table 4.2 by different orders of pairwise comparison matrices. If the value of the CR is below 0.1, it indicates that the comparison judgment in performing the importance scale doesn't consist of randomness and finally the evaluation of the importance degrees is acceptable and reasonable.

Table 4.2. Random index (RI) value

Matrix order	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

5. Transform pair wise comparison matrix into triangular fuzzy number according to the table 4.3.

$$\tilde{\boldsymbol{A}} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{n1} & 1/\tilde{a}_{n2} & \cdots & 1 \end{bmatrix}$$

where $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$; $\forall$i,j= 1,2,…,n

and $\tilde{a}_{ij} = \begin{cases} 1 \; if \; i = j \\ \tilde{9}, \tilde{8}, \tilde{7}, \tilde{6}, \tilde{5}, \tilde{4}, \tilde{3}, \tilde{2} \; or \; its \; reciprocal \; if \; i \neq j \end{cases}$

Table 4.3. Triangular fuzzy numbers based on the Saaty's scale

Fuzzy Number	Fuzzy Triangular Number (l.m.u)	Reciprocal Fuzzy Number	Reciprocal Fuzzy Triangular Number
$\tilde{1}$	(1,1, 1)	$1/\tilde{1}$	(1,1, 1)
$\tilde{2}$	(1, 2, 3)	$1/\tilde{2}$	(1/3, 1/2, 1)
$\tilde{3}$	(1, 3, 5)	$1/\tilde{3}$	(1/5, 1/3, 1)
$\tilde{4}$	(2, 4, 6)	$1/\tilde{4}$	(1/6, 1/4, 1/2)
$\tilde{5}$	(3, 5, 7)	$1/\tilde{5}$	(1/7, 1/5, 1/3)
$\tilde{6}$	(4, 6, 8)	$1/\tilde{6}$	(1/8, 1/6, 1/4)
$\tilde{7}$	(5, 7, 9)	$1/\tilde{7}$	(1/9, 1/7, 1/5)
$\tilde{8}$	(6, 8, 9)	$1/\tilde{8}$	(1/9, 1/8, 1/6)
$\tilde{9}$	(7, 9, 9)	$1/\tilde{9}$	(1/9, 1/9, 1/7)

6. Aggregate the elements of synthetic fuzzy pairwise comparison matrix for criteria ($\tilde{a}_{ij}$) and sub-criteria ($\tilde{a}_{lj}$) judged by K-decision maker by using the geometric mean method suggested by Buckley (1985). To perform the operation of two fuzzy numbers, table 4.4 is shown.

$$\tilde{a}_{ij} = (\tilde{a}_{ijk} \otimes \ldots \otimes \tilde{a}_{ij2} \otimes \ldots \otimes \tilde{a}_{ijK})^{1/K}$$
$$\tilde{a}_{lj} = (\tilde{a}_{lk} \otimes \ldots \otimes \tilde{a}_{lj2} \otimes \ldots \otimes \tilde{a}_{ljK})^{1/K} \quad (4.5)$$
$$\tilde{a}_{mj} = (\tilde{a}_{mjk} \otimes \ldots \otimes \tilde{a}_{lj2} \otimes \ldots \otimes \tilde{a}_{mjK})^{1/K}$$

Table 4.4. the algebraic operations of any two fuzzy numbers $\tilde{a}_1$ and $\tilde{a}_2$

Fuzzy Operation	Fuzzy formula	Calculation Operation
Fuzzy addition	$\tilde{a}_1 \oplus \tilde{a}_2$	$(l_1 + l_2, m_1 + m_2, u_1 + u_2)$
Fuzzy subtraction	$\tilde{a}_1 \ominus \tilde{a}_2$	$(l_1 - u_2, m_1 - m_2, u_1 - l_2)$
Fuzzy multiplication	$\tilde{a}_1 \otimes \tilde{a}_2$	$(l_1.l_2, m_1.m_2, u_1.u_2)$
Fuzzy division	$\tilde{a}_1 \oslash \tilde{a}_2$	$(l_1/ u_2, m_1/ m_2, u_1/ l_2)$

7. Calculate fuzzy weight for each criterion ($\tilde{w}_i$) and sub-criterion ($\tilde{w}_l$)

$\widetilde{w}_i = \tilde{r}_i \oslash [\tilde{r}_1 \oplus \ldots \oplus \tilde{r}_i \oplus \ldots \oplus \tilde{r}_n]$

$\widetilde{w}_l = \tilde{r}_l \oslash [\tilde{r}_1 \oplus \ldots \oplus \tilde{r}_l \oplus \ldots \oplus \tilde{r}_L]$ (4.6)

where:

$\tilde{r}_i = (\tilde{a}_{i1} \otimes \ldots \otimes \tilde{a}_{ij} \otimes \ldots \otimes \tilde{a}_{in})^{1/n}$

$\tilde{r}_l = (\tilde{a}_{l1} \otimes \ldots \otimes \tilde{a}_{lj} \otimes \ldots \otimes \tilde{a}_{lL})^{1/L}$

8. Obtain crisp value of criteria (w_i) and sub-criteria (w_l) weight to find out the importance order based on the crisp value from high to small. COG (Center Of Gravity) is introduced to derive a crisp value in view of simplicity and efficiency (Pan, 2008). COG formula can be expressed as follows:

$$Z^* = \frac{\int \mu (Z).Z \, dz}{\int \mu(Z) dz} \quad (4.7)$$

where μ(Z) is the membership value; Z^* is the weighted average

9. Compute global weight of each sub-criterion (W_j)

$W_j = w_i \otimes w_l$; l= 1,2,…, L; i=1,2,…,n; j =1,2,…, L (4.8)

3.1.2 Objective Weight: Entropy weight

In general, multi criteria decision making (MCDM) deals with evaluation, measurement and selection of alternatives based on some criteria The weight of the criteria are important to be measured because each criterion evaluation is not equal importance. It gives a significant influence to the overall value of alternatives. Weight of criteria can be generalized into two categories namely subjective and objective weight. Subjective weight is determined by opinion of experts which relies on the knowledge and experience. Objective weight is initialized based on the statistical properties and measurement data. There are several techniques to obtain the weight, such as the weight evaluation technique, the eigenvector method, the weighted least square method, the entropy method, AHP method and so on (Huang, 2008).

The concept of deriving the weight based on the entropy method is appraising the weight without the direct involvement of the decision makers. It admits that the importance of a criterion is the direct function of information conveyed by it relative to the whole set of alternatives. Applying entropy on deriving weight is based on the idea that a criterion is more important if there is a greater dissemination in the evaluations of the alternatives. The superiority of applying entropy method for obtaining the weight of a criterion is that it avoids subjectivity of decision makers in determining the weight but includes the objective assessment instead and it gives an advantage when decision makers conflict on the values of weights (Song et al., 2013).

In this paper, entropy weight is introduced to derive objective weight. The weight is determined based on the entropy information and historical raw data. According to the information theory, entropy is a measure for the amount of uncertainty in a random variable and for instance, a measure of uncertainty of information content. Whereas, in thermodynamics, entropy can be defined as a measure of the number of specific ways in which a thermodynamic system may be arranged or a measure of progressing towards thermodynamic equilibrium.

Definition 1.

In information theory, Shannon introduced entropy in 1940 which is denoted by H. It is derived from a discrete random variable of X with possible values $\{x_{1,}\ldots, x_n\}$ with probability mass function of P(X). H is initially suggested as Boltzman's H-theorem. Based on the shannon's entropy, H can be expressed as,

$$H\ (X) = E\ [I\ (X)] = E\ [-\ln\ (P(X))]$$

where,

E = expected value of operator

I = Information content of random variable X

X = a random variable

For a finite data, a random variable X with n outcomes $\{x_1,\ldots, x_n\}$, uncertainty of random variable can be measured with definition of H which is defined as

$$H\ (X) = -\sum_{i=1}^{n} p(x_i)\ log_b p(x_i)$$

where $p(x_i)$ is probability mass function of outcome x_i

Shannon's entropy is characterized (in mathematical terminology) by a small number of criteria and any definition of entropy which satisfies the assumptions has the general form as

$$H(X)= H(p_1,\ \ldots,\ p_{n)} = -K\sum_{i=1}^{n} p_i \log(p_i)$$

where K is a constant corresponding to a choice of measurement units

Definition 2.

In statistical thermodynamics, entropy is most generally denoted by S. According to the Gibbs entropy in the 1870s, the entropy S is defined as

$$S = -K\sum_{i=1}^{n} p_i \ln(p_i)$$

where,

K = Boltzmann constant

p_i = the probability of a microstate i taken from an equilibrium ensemble

Entropy is widely adopted for deriving objective weight in multi criteria decision making problems. Entropy is used to determine the weight of criteria for e-commerce website evaluation based on TOPSIS & FAHP (Chen, et al., 2012). Xin (2010) attempted to find an optimized model of decision making proposal for nuclear emergency based on the entropy weight. Ghorbani et al., (2012) implemented entropy for selecting supplier and allocating order by combining SWOT and mathematical programming. Hsu (2013) evaluated financial performance by using TOPSIS and the weight of evaluation criteria influencing the financial performance is obtained by using entropy. Abdulllah & Otheman proposed new objective weight for sub-criteria in interval type-2 fuzzy TOPSIS. The objective weight is determined based on the entropy and the new approach is applied within the entropy estimation to conform the trapezoidal fuzzy number. Evaluation of synchronized supply chain performance from power equipment limited company in Shanghai is performed by Li & Wang (2011). In their study, entropy weight and TOPSIS are proposed as an effective method. The study conducted by Huang (2008) proposed a combination of entropy weight to obtain the objective weight of evaluation criteria and TOPSIS for information system selection.

Song et al., (2013) analyzed failure modes and effects in different phase of product life cycle by using integrated weight-based fuzzy TOPSIS. They consider both subjective criteria and objective criteria by integrating the weight of those criteria into one. Weight of subjective criteria is obtained based on the experts' opinion. Entropy is used to calculate objective weight and the final weight obtained is a combined weight of both subjective and objective weight.

The study came up with an issue about supplier evaluation and selection under the context of reducing carbon emissions thorough out a supply chain is performed by Lin et al., (2010). Evaluation and selection of supplier are established by using TOPSIS based on entropy weight. The original data are used to evaluate the criteria.

Ding (2011) proposed an integrated fuzzy TOPSIS method and demonstrated the computational process for integrating objective weight derived based on entropy and subjective weight derived based on decision maker's opinion within the procedure of hierarchical fuzzy TOPSIS.

In this study, Objective weight is obtained by using entropy method. Entropy is adopted and deployed in its procedure according to the decision matrix dealing with assessment of alternatives under each criterion. Calculation of objective weight of sub-criteria above the alternative level by using entropy method can be summarized as follows:

1) Construct decision matrix

Consider that there are m alternative, n evaluation criterion, and k historical data. If the historical data indicates some various values, the triangular fuzzy number of the data (l, m, u) can be constructed by using geometric mean method. The fuzzy value of historical data corresponding m alternatives versus n objective sub-criteria above the alternatives layer can be determined by using procedure described as follows:

$$l = \min_i \{x_{ij}\}$$

$$m = \left(\prod_{i=1}^{k} x_i\right)^{\frac{1}{k}} \qquad (4.9)$$

$$u = \max_i \{x_{ij}\}$$

Obtain the original fuzzy evaluation value $\tilde{x}_{ij}$ of alternative A_i under sub-criterion C_j according to k historical data. Then fuzzy decision matrix can be expressed as:

$\widetilde{\mathbf{D}} = [\tilde{x}_{ij}]_{mxn}$, i = 1,2,…, m ; j = 1,2,…, n

2) Normalize fuzzy decision matrix

Dealing with benefit criterion which the greater is the better and cost criteria which the less is better, the original fuzzy evaluation value $\tilde{x}_{ij}$ should be converted to dimensionless index through normalization. Normalized fuzzy decision matrix is denoted by $\widetilde{\mathbf{R}}$ which can be obtained from:

$\widetilde{\mathbf{R}} = [\tilde{r}_{ij}]_{mxn}$, i = 1,2,…, m ; j = 1,2,…, n

The formula above can be calculated as details:

- for benefit sub-criterion above alternative layer

$\tilde{r}_{ij} = \left(\frac{l_{ij}}{U_j^*}, \frac{m_{ij}}{U_j^*}, \frac{u_{ij}}{U_j^*}\right)$, where $U_j^* = \max u_{ij}$

- for cost sub-criterion above alternative layer

$\tilde{r}_{ij} = \left(\frac{l_j^*}{u_{ij}}, \frac{l_j^*}{m_{ij}}, \frac{l_j^*}{l_{ij}}\right)$, where $l_j^* = \min l_{ij}$

The normalization method bounds the original fuzzy evaluation value between 0 and 1. After obtaining the fuzzy normalized for each sub-criterion. Then, the crisp value of normalized weight is expressed by r_{ij}. Center of gravity method (COG) is applied to derive crisp value of fuzzy evaluation weight of sub-criteria. Here, we can define

$$R_j = \sum_{i=1}^{n} r_{ij}$$

3) Calculate the entropy value of each criterion

The entropy value of E_j for each sub-criterion under the objective evaluation j can be calculated by using formula as follows:

$$E_j = -k \sum_{i=1}^{n} p_{ij} \ln p_{ij}$$

$$E_j = -k \sum_{i=1}^{n} \frac{r_{ij}}{R_j} \ln \frac{r_{ij}}{R_j} \tag{4.10}$$

where k = $\frac{1}{\ln n}$, k > 0 ; 0 ≤ E_j ≤ 1

4) Calculate the degree of diversification from entropy value

The diversification degree of entropy value is determined as follows:

$$d_j = 1 - E_j \quad ; j = 1,2,\ldots,n \tag{4.11}$$

Diversification degree d_j represents the inherent contrast intensity of sub-criterion j. The higher the diversification degree is, the more important the criterion is.

5) Obtain objective weight based on the entropy

The objective weight w_{oj} of j^{th} sub-criterion above the alternative level can be calculated by using the equation bellow:

$$w_{oj} = \frac{d_j}{\sum_{k=1}^{n} d_j} = \frac{1 - E_j}{\sum_{i=k}^{n}(1 - E_j)} \tag{4.12}$$

$$0 \leq w_{oj} \leq 1; \sum_{i=1}^{n} w_{oj} = 1$$

3.1.3 Integration of Weight (Subjective & Objective Weight)

In order to take notice the importance of criteria and consider the experience of the decision makers, it is essential to integrate the subjective weight from decision makers' judgment and objective weight obtained from entropy weight. The integration aims to gain a comprehensive determination of criteria weight. To affirm the difference risk among the criteria, objective and subjective weight are integrated by using multiplication approach which is derived through multiplying the objective entropy weight and subjective weight and then normalizing the value.

The procedure of integrating the weight can be written as follows (Ding, 2011):

$$W_j = \frac{w_{sj} x\, w_{oj}}{\sum_{j=1}^{n} w_{sj} x\, w_{oj}} x \sum_{j=1}^{n} w_{sj} \qquad , j = 1,2,\ldots, n \tag{4.13}$$

Where,

w_{sj} = subjective weight of j^{th} sub criterion obtained from decision makers' judgment

w_{oj} = objective weight of j^{th} sub criterion obtained from entropy method

W_j = integrated weight of j^{th} sub criterion

3.2 Hierarchical Fuzzy TOPSIS

Hwang and Yoon (1981) was proposed TOPSIS (technique for order preference by similarity to an ideal solution). In TOPIS, the best alternative is selected according to the one which indicates farthest distance from Negative Ideal Solution (NIS) or in other words the one which indicates shortest distance from Positive Ideal Solution (PIS). In the environment under uncertainty and vagueness, TOPSIS is combined with fuzzy theory for carrying out the opinion of decision maker into fuzzy preferences. Several studies in terms of decision making and performance evaluation have been conducted by applying fuzzy TOPSIS to solve the problem under uncertain environment. Some of them developed TOPSIS by transforming the importance scale into triangular fuzzy number (Yazdani,2012; Sun&Lin,2009; Izadikhah et al., 2006; Chu, 2002; Chen, 2000) and into trapezoidal fuzzy number (Mohammadi et al.,2011; Yazdian& Shahanaghi,2009). TOPSIS was combined with another method since the evaluation of the problem is more complex and the comprehensive decision is required. Past studies adopted an integrated TOPSIS with another method under fuzzy environment such as ANP (Mohaghar et al., 2012; Shemshadi et al., 2011; Önüt et al., 2008), MCGP (Erdebilli & Saputro;2014), AHP (Kutlu& Ekmekçiog˘lu, 2012; Sun, 2010; Ballı& Korukoğlu,2009), and MOMILP (Jadidi et al., 2008).

To deal with alternative selection, fuzzy TOPSIS is adopted. In this study, weight of evaluation criteria is derived from fuzzy AHP. The steps of hierarchical fuzzy TOPSIS can be described into details as follows:

1) Generating feasible alternatives, determining the evaluation criteria, and setting a group of decision makers. Assume that there are m alternative, L evaluation criterion, and k decision maker.

2) Obtain global weight of sub criteria ($\widetilde{W}_j$) (under the corresponding $i^{\text{-th}}$ criterion) by using fuzzy AHP (see session 3.1.1).

3) Choose the appropriate linguistic ratings for alternatives with respect to criteria ($\tilde{x}_{ij}$) as TFN.

4) Obtain the aggregated fuzzy rating $\tilde{x}_{ij}$ of alternative A_i under sub-criterion C_j (under the corresponding $i^{\text{-th}}$ criterion) evaluated by k expert.

$$\tilde{x}_{ij} = \frac{1}{k} [\, \tilde{x}_{ij}^{1} + \tilde{x}_{ij}^{2} + \ldots + \tilde{x}_{ij}^{k} \,] \; ; i = 1,2, \ldots, m \; ; j = 1,2, \ldots, L \qquad (4.14)$$

5) Construct the fuzzy decision matrix.

$$\widetilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \end{array} \; ; i = 1,2, \ldots, m \; ; j = 1,2, \ldots, L$$

6) Normalize fuzzy decision matrix.

The normalized fuzzy decision matrix denoted by $\tilde{R}$ is obtained by formula as follows:

$$\widetilde{\mathbf{R}} = [\tilde{r}_{ij}]_{mxn} \quad , i = 1,2,\ldots, m \; ; \quad j = 1,2,\ldots, L$$

The formula above can be calculated as details:

for benefit sub-criterion above alternative layer

$$\tilde{r}_{ij} = \left(\frac{l_{ij}}{U_j^*}, \frac{m_{ij}}{U_j^*}, \frac{u_{ij}}{U_j^*}\right), \text{ where } U_j^* = \max u_{ij}$$

for cost sub-criterion above alternative layer

$$\tilde{r}_{ij} = \left(\frac{l_j^*}{u_{ij}}, \frac{l_j^*}{m_{ij}}, \frac{l_j^*}{l_{ij}}\right), \text{ where } l_j^* = \min l_{ij}$$

7) Construct the weighted normalized fuzzy decision matrix.

In order to the different importance of each criterion, we can construct the weighted normalized fuzzy decision matrix as:

$$\widetilde{\mathbf{V}} = [\tilde{v}_{ij}]_{mxn} \quad , i = 1,2,\ldots, m \; ; \quad j = 1,2,\ldots, L \qquad (4.15)$$

Where $\tilde{v}_{ij} = \tilde{r}_{ij} \otimes W_j$, i = 1,2,…, m ; j = 1,2,…, L and W_j[1] is the global weight of sub-criterion.

The weights of subjective and objective sub-criteria above the alternatives layer are obtained by using different method. The subjective weight is obtained by using fuzzy AHP and the objective weight is obtained by using entropy method. Because the problem contains 2 different weight categories, thus, we have to be clear with the conditions in which the weight is derived from and whether should be applied. To deal with those conditions, some cases are necessary to be paid attention:

a) Condition I

   If the problem consists of only subjective (sub) criteria, then use fuzzy AHP approach to obtain the weight (W_j).

b) Condition II

   If the problem consists of only objective (sub) criteria, then use the entropy weighting method (W_j).

c) Condition III

   If the problem consists of both objective and subjective sub-criteria, then, use the integration weight (W_j).

8) Determine the fuzzy positive-ideal solution (FPIS) S^+ and fuzzy negative-ideal solution (FNIS) S^-. The formula can be obtained as follows:

$$S^+ = (\tilde{v}_1^+ , \tilde{v}_2^+ , \dots, \tilde{v}_n^+)$$

$$S^- = (\tilde{v}_1^- , \tilde{v}_2^- , \dots, \tilde{v}_n^-)$$

where $\tilde{v}_j^+$ = max $\{v_{ij3}\}$ and $\tilde{v}_j^-$ = min $\{v_{ij1}\}$ since $\tilde{v}_j$ is weighted normalized TFNs i = 1,2,…, m ; j = 1,2,…, L

9) Calculate the distance of each alternative from FPIS (d^+) and FNIS (d^-) .

According to the vertex method, the distance between two triangular fuzzy numbers A_1 (l_1, m_1, u_1) and A_2 (l_2, m_2, u_2) is calculated as:

---

[1] W_j is weight of sub-criteria obtained by using fuzzy AHP.

$$d(A_1, A_2) = \sqrt{\frac{1}{3}\left[(l_1 - l_2)^2 + (m_1 - m_2)^2 + (u_1 - u_2)^2\right]}$$

$$d_i^+ = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^+\right), \quad i = 1,2,\ldots, m \qquad (4.16)$$

$$d_i^- = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^-\right), \quad i = 1,2,\ldots, m$$

10) Calculate the closeness coefficient (CC_i) and rank the order of alternatives according to the coefficient.

After we obtain the distance d^+ and d^-, we calculate the closeness coefficient of each alternative using the formula bellow:

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-}, \quad i = 1,2,\ldots, m \qquad (4.17)$$

Based on the value of closeness coefficient of each alternative, we determine the ranking order of all alternatives from the highest closeness coefficient to the lowest. The alternative with the highest closeness coefficient is obviously considerable.

There are a number of specific procedures that can be used for Step 2 (developing weights), and for Step 8 (distance measures) (Olson, 2004). Additionally, different conventions can be applied to define the FPIS and FNIS (Olson, 2004).

CHAPTER 5

MULTI-OBJECTIVE OPTIMIZATION

5.1 Augmented ε-constraint Method

Augmented ε-constraint method, known as AUGMECON, was developed by Mavrotas (2009). The method was proposed to improve the implementation of ε-constraint method in multi-objective optimization. The traditional ε-constraint method was originally introduced by Chankong and Haimes in 1983.

There are some superiorities of ε-constraint method toward weighting method which are explained in the following:

1. In the linear case, the weighting method generates only efficient extreme solution since the original feasible region is applied and a corner solution (extreme solution) eventuates in the final result. While the e-constraint method modifies the original feasible region and the result would be non-extreme efficient solutions. In addition, weighting method may carries out the choices of weight combination, that the results would may be same efficient extreme solution and it would be redundant in running each combination.
2. The weighting method cannot affirm multi-objective integer and mixed integer programming problems in producing solution, whereas the e-constraint method can stand well to tackle it (Steuer 1986, Miettinen 1999).
3. The weighting method requires scaling the objective functions that is converted into a common scale, while the e-constrained method doesn't need to scale the objective functions.
4. Furthermore, unlike weighting method, the number of the generated efficient solutions can be controlled properly by customizing the number of grid points in each one of the objective function ranges in the ε-constraint method.

Let's consider a set of multi-objective problems based on the original ε-constraint formula to illustrate transformation of augmented ε-constraint method, by supposing there are *n* objective functions. Shortly we have problem P (e_j) as follows:

$\text{Min } f_j(x), \{f_1(x), f_2(x), \dots, f_n(x)\}$

$\text{st } f_i(x) \leq e_i, \forall i \in \{1,2,\dots, n\} / \{j\}$

$x \in S,$

where x represents set of decision variables, $f_1(x)$, $f_2(x)$, …, $f_n(x)$ are objectives functions and feasible region is shown by S.

Proof: *If an objective j and a vector* $e = (e_1, \dots, e_{j-1}, e_{j+1}, \dots, e_n) \in R^{n-1}$ *exist, then* x^* *is a weak pareto optimum;* x^* *is a strict pareto optimum if and if for each objective j {j= 1, …, n}, there exists a vector* $e = (e_1, \dots, e_{j-1}, e_{j+1}, \dots, e_n) \in R^{n-1}$ *such that* $f(x^*)$ *is the unique objective vector corresponding to the optimal solution to problem P (e).*

According to the ε-constraint method, we are interested in one among existed objectives functions to be prioritized for optimization and add the remaining objective functions to the constraints. For example, we would like to minimize $f_1(x)$ as objective function. The problem P (e_1) can be written as follow:

$\text{Min } f_1(x)$

st

$f_2(x) \leq e_2$

$f_3(x) \leq e_3$

…

$f_n(x) \leq e_n$

$x \in S$

The efficient solutions of the problem are obtained by controlling e_i as RHS of constrained objective functions. One advantage of the ε -constraints method is that it is able to achieve efficient points in a non-convex Pareto curve. But from another side, the method is not particularly efficient if the number of the objective functions is greater than two. Hence, augmented ε-constraint method is proposed in order to apply the ε-constraint method properly by first determining the range of each objective function, at least for the n-1 objective functions that will be used as constraints. In easy procedure, the range of the objective function can be calculated according to the values derived from payoff table finding the optimal solution for individual objective function. To be sure that the individual optimization of the objective functions are derived to Pareto optimal solution, then lexicographic method highly is suggested to withdraw the individual optimization values into payoff table.

In addition, the individual optima using conventional LP optimizer results likely a dominated solution, which that is obtained through calculating the solution of point P first and will stop the searching giving this solution as output (Mavrotas, 2009).

In general, the lexicographic optimization orders n objective functions into hierarchy. The first steps is optimize one that is most important objective function among others and the result is obtained, the second important objective function is searched for then, and so forth until the last objective function has been successfully optimized. By looking at problem P (e_1), the lexicographic optimization is performed as follows:

1. The objective function of $f_1(x)$ is optimized first (most important/highest priority) and the optimum solution (minimum) $f_1 = z_1^*$.
2. Then, optimize objective function of $f_2(x)$ by using value of z_1^* as constraint in order to keep the optimal solution of the objective function of $f_1(x)$, and the optimum solution (minimum) $f_2 = z_2^*$ is obtained.
3. Subsequently, use value of z_1^* and z_2^* as constraints to optimize the objective function of $f_3(x)$, then the optimum solution (minimum) $f_3 = z_3^*$ is obtained.
4. Do the same approach to optimize the n^{th} objective functions by adding optimum solution of all objective functions (n-1) to the constraints. Finally, $f_n = z_n^*$ is obtained.

z_1^*, z_2^*, …, z_n^* are the best value (ideal value), the minimum value for minimization problems, while the maximum value is the best solution for maximization problems. Further, nadir value is the effective value (lower bound in maximization problems and upper bound in minimization problems). By contrast, reservation value is the worst value over the efficient set. Value worse than reservation value is not allowed.

The obtained optimal solution of problem P (e_1) is not literally efficient, but it is a weakly efficient solution, it can be achieved only if all the (n-1) objective functions' constraints are binding (Miettinen, 1998; Ehrgott & Wiecek, 2005). Therefore, equality transformation of objective function constraints must be done by adding slack (s_l) (for maximization problem) or surplus (s_p) (for minimization problem) for the following order of objective functions' constraints in the same time. Thus, the problem P (e_1) is transformed becomes:

$$\text{Min } (f_1(x) + eps \times (s_{p2} + s_{p3} + \ldots + s_{pn}))$$

st

$f_2(x) + s_{p2} = e_2$

$f_3(x) + s_{p2} = e_3$

…

$f_n(x) + s_{pn} = e_n$

$x \in S$ and $s_i \in R^-$

where *eps* is a small number (usually between 10^{-3} and 10^{-6})

s_i in the second term of objective function will be replaced by s_i/r_i in order to avoid any scaling problems. Where r_i is the range of the i^{th} objective function which is calculated from the payoff table. Finally, the problem is intact transformed into augmented ε-constraint in the following:

$$\text{Min } (f_1(x) + eps \times (s_{p2}/ r_2 + s_{p3}/ r_3 + \ldots + s_{pn}/ r_n))$$

st

$f_2(x) + s_{p2} = e_2$

$f_3(x) + s_{p3} = e_3$

…

$f_n(x) + s_{pn} = e_n$

$x \in S$ and $s_i \in R^-$

5.2 Developing Optimization Model for MHE Selection

In this thesis, the optimization model for MHE selection problem in warehouse is built according to multi-objective integer linear programming. Regardless of positioning, unit load formation, storage, and identification and control equipment, this problem is focused on selecting transport equipment, particularly for industrial truck, which is generally used within some warehouse operations such as putt-away, picking in batch, loading and etc. This model aims to find the best MHE in order to achieve the optimum solution by considering some objective functions and constraints.

In view of a sophisticated decision making, MHE is selected by considering both tangible and intangible criteria. Therefore, we use evaluation based analytic for

MHE alternatives that would be included in the optimization model to incorporate those criteria. Here, TOPSIS is proposed as analytic method for constructing the evaluation weight corresponding to each alternative.

We develop MOMILP according to the real case adapted from a manufacturer where it applies specific circumstances as follows:

1) MHE selection problem is highlighted to intermediate level.
2) MHE is focused on warehouse operation for finished-good product.
3) The materials handled are homogenous products.
4) Permissible load for MHE is regulated by warehouse authority because the product is perishable. On the other hand, in order to handle product safely, the maximum load should respect the authority rather than load capacity of MHE itself.

The notations are defined to formulate the model:

Indices:

i = 1,2,…n index for MHE

Parameters:

MC_i	= Maintenance cost of MHE i per day
OC_i	= Operation cost of MHE i per minute
P_i	= Purchase cost of MHE i
S_i	= Savage value of MHE i in the expected life year
F_i	= Expected life of MHE i
D_{store}	= Average of product received in warehouse (per day)
D_{ship}	= Average of product shipped to customer (per day)
E_i	= Maximum load capacity of MHE i (kg)
E_{max}	= Permissible load (kg)
$LULT_{store,i}$	= Loading unloading time per move of received-product using MHE i (minute)
$LULT_{ship,i}$	= Loading unloading time per move of delivered-product using MHE i (minute)
$T_{store,\ i}$	= Travel time per trip of received-product with load using MHE i to storage area (minute)

$T_{ship,\, i}$ = Travel time per trip of delivered-product with load using MHE i to shipping area (minute)

$t_{store,\, i}$ = Travel time per trip of received-product without load using MHE i to receiving area (minute)

$t_{ship,\, i}$ = Travel time per trip of delivered-product without load using MHE i to storage area (minute)

CC_i = Rating of MHE i (is the closeness coefficient obtained from entropy based hierarchical fuzzy TOPSIS)

h_i = Lift height of MHE i (meter)

H_i = Body height of MHE i (meter)

b_i = Width of MHE i with load (meter)

$H_{storage}$ = Height of storage (meter)

L = Width of aisle (meter)

TH = Total available work hour per day (minute)

$A_{st,i}$ = Aisle for 90^0 stacking (meter)

U = Utility of time

Decision variables:

Y_i = 1, if MHE i is selected

0, otherwise

X_i = Number of MHE i

Objective functions:

Minimize disadvantages of use Z_1 (X,Y)

Min $\sum_{i=1}^{n}(1 - CC_i).E_{max}.X_iY_i$, i =1,2,…n (1)

Minimize total cost of material handling Z_2 (X,Y)

$$\text{Min} \sum_{i=1}^{n} X_i.Y_i(\left(\frac{P_i - S_i}{F_i}\right) + MC_i) + \sum_{i=1}^{n} (\frac{D_{store}.(\text{LULTstore, i} + \text{Tstore, i} + \text{tstore, i}) + D_{ship}.(\text{LULTship, i} + \text{Tship, i} + \text{tship, i})}{X_i E_{max}}) OC_i \,.Y_i$$

, i =1,2,…n (2)

Objective function (1) aims to minimize disadvantages of use ($1-CC_i$) from selected MHE. On the other hand, this objective function ensures to achieve maximum value of use (CC_i) from selected MHE. Disadvantages of use are measured involving some tangible and intangible criteria. In order to incorporate this objective, alternative rating (CC_i) derived from TOPSIS method is constructed in the model so that selected MHE can contribute some benefits with respect to every loaded material during handling operation. Objective function (2) guarantees that the selected MHE can provide minimum total cost of material handling. Cost parameters involve depreciation cost, maintenance cost and operation cost (fuel/energy and labor cost). Depreciation cost is calculated by using straight line method which can be expressed as:

$$\text{Depreciation cost of MHE} = \frac{Purcahse\ cost - Salvage\ value}{Expected\ life} = \frac{P_i - S_i}{F_i}$$

Constraints:

$\sum_{i=1}^{n} Y_i = 1$, i =1,2,…n (3)

$U.TH \leq \sum_{i=1}^{n} Y_i \left(\frac{D_{store}.(\text{LULTstore,i+Tstore,i+tstore,i}) + D_{ship}.(\text{LULTship,i+Tship,i+tship,i})}{X_i E_{max}} \right) \leq TH$, i =1,2,…n (4)

$\sum_{i=1}^{n} Y_i . h_i \geq H_{storage}$, i =1,2,…n (5)

$\sum_{i=1}^{n} Y_i . b_i \leq L$, i =1,2,…n (6)

$\sum_{i=1}^{n} Y_i . E_i \geq E_{max}$, i =1,2,…n (7)

$\sum_{i=1}^{n} Y_i . A_{sti} \leq L$, i =1,2,…n (8)

Constraint (3) allows only one MHE to be selected. Constraint (4) describes the number of selected MHE should be appropriately determined so that it can fulfill the material handling operation within the available work hour per day and to avoid high number of MHE in idle. The number of idle and busy MHE should be balance in order to offer optimum utilization. Constraint (5), (6), (8) ensure the flexibility and compatibility of selected MHE in view of warehouse space. Constraint (5) ensures the lift height of MHE is able to reach the maximum storage height when picking or storing the material. Constraint (6) ensures MHE is able to travel through the aisle. Constraint (7) is to ensure MHE possible to load material up to maximum weight allowed by warehouse authority.

Constraint (8) is intended to deal with the bound of turning radius (W_a) of MHE among the storage aisles (see figure 5.1). For industrial truck, there are two kinds of turning radius which are inside and outside. The outside radius is measured by the overall swing of the truck frame to the furthest point of the rear frame and the inside radius or the pivot point can be estimated between 0.0762 and 0.1016 meters outside the truck drive wheels (front wheels) (John Snow. Inc., 2005). Turning radius (W_a) is one of the considered parameters in order to produce convenient movement when stacking is performed between aisles. In general, stacking is performed at 90^0 right turn angle. Constraint (8) ensures that required aisle for stacking meets the available aisle. Aisle for 90^0 stacking may vary depends on the industrial truck type. For common industrial trucks, stacking aisle can be calculated as follows:

- Pallet Truck and Low Level Order Picker

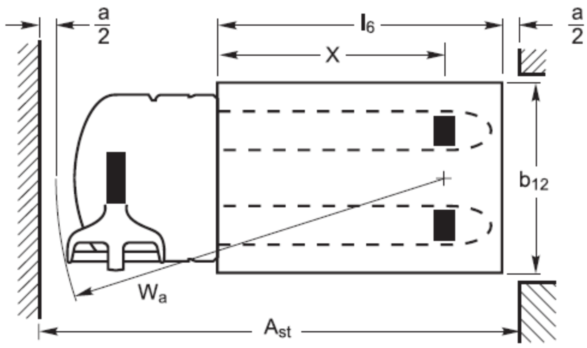

Figure 5.1 Dimensions of Pallet Truck and Low Level Order Picker

$A_{st} = W_a - x + l_6 + a$

- Pallet stackers and Reach Trucks –Reach in

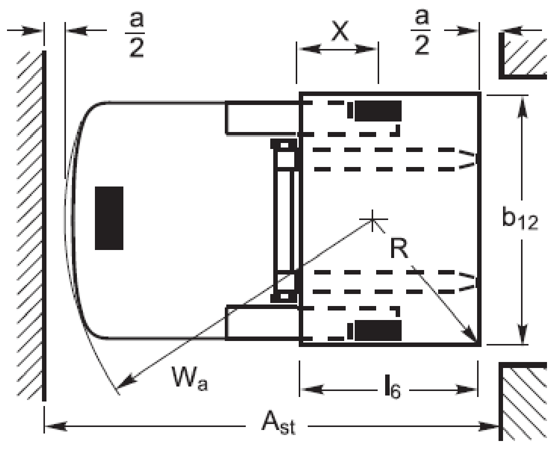

Figure 5.2 Dimensions of Pallet stackers and Reach Trucks

$A_{st} = W_a + \sqrt{(l_6 - x)^2 + \left(\frac{b_{12}}{2}\right)^2} + a$

- Counterbalance trucks (E) - three-wheeled, close coupled steer or combi axle, reach trucks (R) - reach out

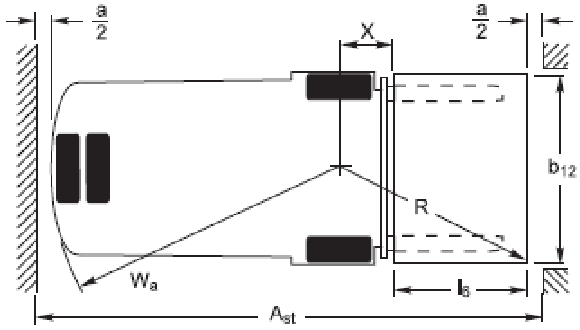

Figure 5.3 Dimensions of Counterbalance trucks (E) - three-wheeled

$A_{st} = W_a + \sqrt{(l_6 + x)^2 + \left(\frac{b_{12}}{2}\right)^2} + a$

- Counterbalance trucks (E and H) - four-wheeled with standard load ($\frac{b_{12}}{2} \leq b_{13}$)

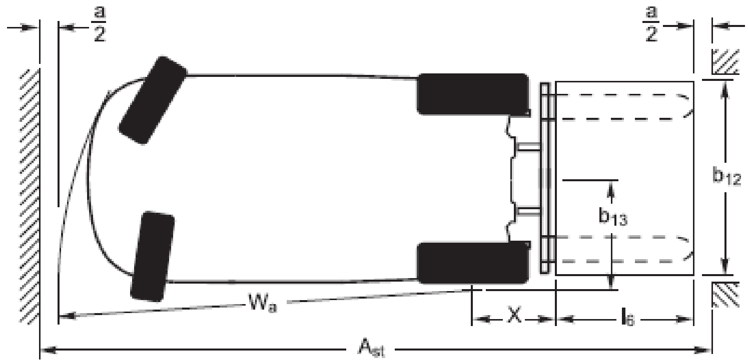

Figure 5.4 Dimensions of Counterbalance trucks (E and H) - four-wheeled

$A_{st} = W_a + x + l_6 + a$

- Counterbalance trucks (E and H) - four-wheeled with wide load ($\frac{b_{12}}{2} > b_{13}$)

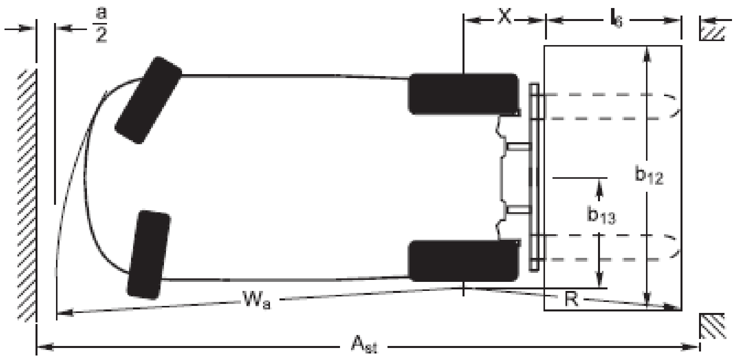

Figure 5.5 Dimensions of Counterbalance trucks (E and H) - four-wheeled

$$A_{st} = W_a + \sqrt{(l_6 + x)^2 + \left(\frac{b_{12}}{2} - b_{13}\right)^2} + a$$

where:

A_{st} = 90^0 stacking aisle	b_{12} = Load width
W_a = Turning radius	b_{13} = Min pivoting point distance
R = Load radius	x = Axle center to fork face
l_6 = Load length	a =Operating clearance[2] (200mm)

Non-negativity and binary constraints:
$X_i \geq 0$ and Integer, i= 1,2,..,n (9)
Y_i = 0 or 1, i=1,2,…,n (10)

Constraint (9) is set to obtain positive and integer value of the number of MHE. Constraint (10) is to deal with the decision whether MHE i is selected or not.

[2] In the general practice, a 200 mm dimension is estimated to enable comparison between different trucks designs and sizes. The same dimension is also adopted by FEM (Federation Europeenne De La Manutention) & BITA (British Industrial Truck Association).

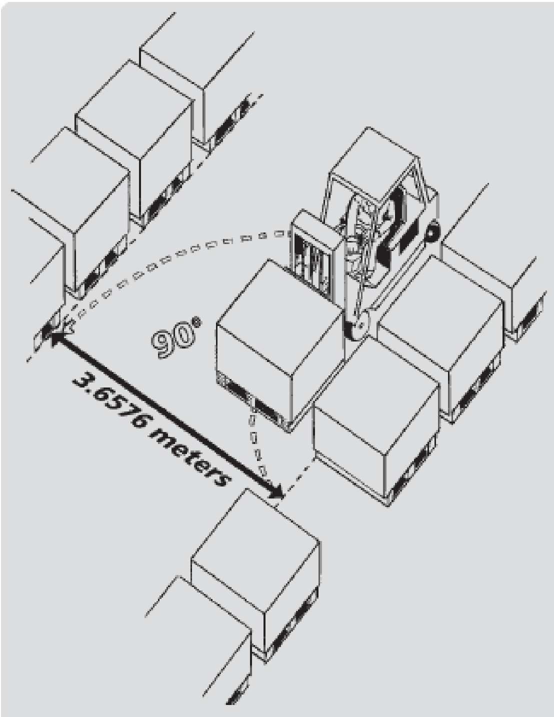

Figure 5.1. Right-angle turning radius

CHAPTER 6
CASE STUDY

6.1 Methodology

MHE selection problem is solved by using a hybrid method that it is an integrated Entropy Based Hierarchical Fuzzy TOPSIS and MOMILP. The hybrid method is proposed to bring a comprehensive decision making in order to find the best MHE for warehouse operations. Multi criteria as well as qualitative and quantitative criteria are incorporated by the hybrid method so that the result of MHE selection can give the high value of use over the expense.

Using several methods such as entropy, fuzzy AHP and fuzzy TOPSIS as a part of methodology for MHE selection problem cannot be apart from massive consideration. Every method is applicable for contributing the evaluation and selection process of MHE. Here, we would like to enlighten the superiority of each method. At first, fuzzy is applied both to AHP and TOPSIS in order to incorporate the uncertain DMs' opinion. In addition, it is caused by evaluation parameters of MHE cannot be precisely measured and predicted. Providing exact numerical values for criteria and making evaluation in exact feeling and recognition within uncertain information and vague human's feeling is literally difficult (Kutlu & Ekmekçiog˘lu, 2012). Hence, fuzzy set theory is performed so that classical AHP and TOPSIS are capable for human's vague thoughts.

AHP is adopted to determine subjective weight in order to provide more measurable criterion weights according to the human judgment within the lack of information. Moreover, we interpret the MHE selection problem in depth evaluation through multilevel structure so that the extension of criteria weight determination can be more selective and AHP is effective to represent this case. Whereas Entropy method is applied for determining objective weight because of the ability to reflect the information essence and measure the useful information of provided data as well as grasps the actual conditions of evaluation criteria (Guo & Zhao, 2014; Zou *et al.*, 2006).

TOPSIS is adopted to evaluate the alternative because it brings some advantages: 1) TOPSIS procedure is matching with selection process of human decision, 2) The algorithm is easy to calculated & implemented, 3) the best and worst solution are considered simultaneously through a scalar value (Hwang & Yoon, 1981), 4) performance measures of alternatives under criteria can be visualized on a polyhedron (Shih *et al*., 2007).

To carry out systematically procedures in this method, methodology is described briefly in the following.

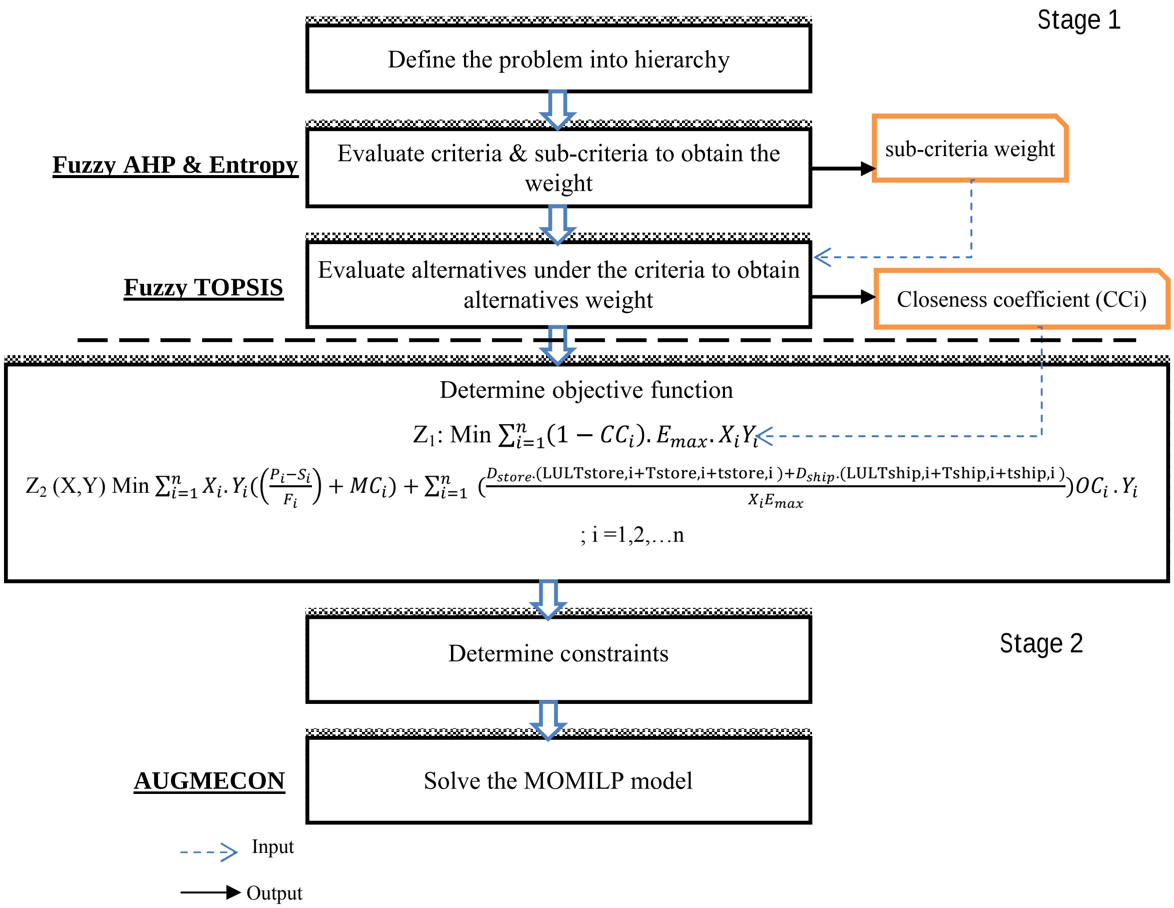

Figure 6.1 Methodology of MHE selection problems

In the first stage, Fuzzy AHP and Fuzzy TOPSIS are applied. The problem will be defined and structured into hierarchy. The problem is defined as multi criteria decision making for MHE selection. To structure the problem, evaluation criteria and alternatives must be determined first. Alternative will be selected according to the relevant criteria, but evaluating alternatives may be distracting because each alternative essentially may have superiority in particular criteria rather than another.

But, the decision maker tends to take for granted the alternative which satisfies the most critical criteria. Therefore, in order to measure overall performance of alternative, determining the criteria weight is required so that the decision making will result the right choice through the right evaluation process. Fuzzy AHP is applied to obtain the criteria weight (procedure is shown in chapter 3 session 3.1). In addition, Shanon's entropy method is introduced in order to obtain the objective weight (see chapter 3 session 3.2). The integration between weight derived from fuzzy AHP and entropy method applies only if the criteria involve subjective and objective evaluation. After the criteria weight has been obtained, then, the next step comes up with evaluating the alternatives with respect to the criteria which is conducted by one or more decision makers. The process of alternative evaluation is done by using fuzzy TOPSIS method (see the procedure in chapter 3 session 3.2).

Second stage, MHE is evaluated objectively by using MOMILP. The evaluation process is conducted as well as optimization approach since the mathematical model covers both tangible and intangible criteria. Initial step in this stage is determine the goals would like to be achieved which incorporate both criteria. The result of MHE selection is expected to be able to give some benefits for the material handled by selected equipment. There are 2 goals, first goal is minimizing disadvantage of use and the second goal aims to minimize total cost of material handling. Disadvantage of use reflects any risk or minority suffered by operator or material itself as a consequence caused by assigning the equipment to handle the material. It will be complicated to measure the disadvantage because the evaluation parameters do seem to be intangible. Hence, the alternatives weight derived from hierarchical fuzzy TOPSIS is integrated to the MOMILP in order to represent the disadvantage of use. Then, we have to determine the boundaries and restrictions exist corresponding to MHE. By adding the constraints appropriately to the model, optimal solution would be reliable. MOMILP is solved according to the AUGMECON procedure by using LINGO software.

6.2 Case Study

6.2.1 Panasonic Lighting Indonesia, Ltd.

Panasonic Lighting Indonesia, Ltd. (PLI), an affiliated manufacturing company, is a leading manufacturer in energy saving lighting with PANASONIC brand. The main products are Straight-tube Fluorescent Lamps and Glass Components. Company has several facilities located in the same site including production plant, QC, warehouse for raw material and finished-good product.

PLI, Ltd. was found on 16 September 1996 as foreign capital investment business. The 100% capital is owned by Matsushita *Electric Corporation* (MEC) dan Matsushita *Electric Industrial* Co.Ltd (MEI). Matsushita *Electric Industrial* Co.Ltd (MEI) is the holding company of PLI, Ltd. which is firslty established by Konosuke Matsushita on 7 March 1981 in Japan with employing 90.000 workers. MEI is a company engaged in electric appliance product and electronic household equipment.

In 1952, MEI Co.Ltd established a subsidiary namely Matsushita Electronic Corporation (MEC) and MEI Co.Ltd is the stockholder with 100% right. MEC Co. Ltd includes 3 company groups which are *semiconductor Group*, *Electron Tube Group*, and *Lighting Group* which producing lamp and PLI is one in it.

The more today's densely population of Indonesia reaching up nearly 245 millions people and the more region's need on lighting, those are stared by Panasonic as a potential market. It trigers Panasonic to invest the capital in Indonesia through opening a lighting company in Pasuruan, East Java which commonly known as Panasonic Lighting Indonesia, Ltd.

The compay's profile of PLI is briefly presented in the following:

- Location: PIER Industrial Estate Jl. Rembang Industri Raya No. 47, Rembang Pasuruan, East Java, Indonesia
- Company's contact: (0343) 740230
- Company's area : 100.920 m^2
- Poduction floor area : 99.975 m^2
- Distribution Center: Jl. Dewi Sartika 14 (Cawang 12), Jakarta, telp. (021) 80880522.
- President director: Takayasu Okamoto

- Number of employee: 2383 people
- Oganization structure:

  There are 3 major structures in the company including:

  1) Engineering Director which is reponsible for organizing the sub-division related to quality analysis.
  2) Production Director including production, supply assembly, and maintenance. This division is grouped according to the product category.
  3) Finance & Admin Director including accounting, HRD, sales, procurement, and planning &cost control.

Figure 6.2. The plant and prodcut variants of Panasonic Lighting Indonesia, Ltd

Its sales number reaches up to 2 million units per month or about 24 million units per year. The market share includes domestic and international sales. The 80% of sales is distributed to Japan and 10% is allocated to fulfill domestic market in Indonesia. While, the rests are spread to ASEAN such as Thailand, Vietnam, Malaysia and Singapore.

PLI really concerns about environmental development literally on energy saving such by pressing production process so that reduce emission nearly 40.000 tons of CO_2. This development makes PLI crowned as a "eco-ideas" leading company in Pasuruan and It becomes a pilot on environmental management for reducing the use of CO_2 globally and regionally.

6.2.2 Data Collection and Results

This issue is focused on the warehouse operation of finished-good product. Warehouse of finished-good product is exclusively stand to store products which are manufactured at production plant. The Product meeting standard quality will be placed in the transfer area before being stored to the warehouse. At that time, product will be checked in order to ensure the model and quantity. Then, finished-good product will be carried to the warehouse and stored into the rack under instructions. The instructions guide the operator to handle the product in safety way by using industrial truck and it must be done appropriately. It deals with some points as follows:

1) Product must be put down on the pallet before it is loaded. The common pallet size used for handling the product is 114 x 90 x 14 cm with net weight 24 kg.
2) Industrial truck can be loaded maximum 2 pallets in the same time due to product's perishability. One pallet with load has a net weight up to 244 kg.

The number of product received in warehouse and shipped from warehouse can be summarized in table 6.1. The average of product in-out per day is equal to 42 pallets and 58 pallets conversion.

Table 6.1. The detail of product in-out per day in March 2014

TYPE	BF	RECEIVED (March 2014)																							
		1	3	4	5	6	7	8	9	10	11	12	13	14	15	17	18	19	20	21	23	24	25	26	27
PREMIER LW	84,070		27,630	29,340	31,010	27,900	11,790		20,850	17,640	32,310	29,530	31,620	25,880	9,840	17,820	35,970	18,540	27,360	29,790	19,530	14,680	14,900	24,660	
PREMIER HW	26,080		2,080	640			2,080		3,360	5,280	4,160	4,640	7,640	7,920	4,640	2,560	5,480	8,360	6,200	4,080	4,160	640	5,520	13,920	
LED	30,550	420	22,430	20,760	19,370	15,370	13,730			22,100	14,790	23,930	17,440	17,380		9,910	24,200	2,656	18,140	18,810		17,000	15,080	22,550	29,130
LCS3 LW	13,710				3,610	8,640	11,600		17,280	5,760	2,880	2,880	8,920	6,480	24,480	17,640	14,400	5,760	3,380	9,000	18,720	14,900	14,900	17,280	
LCS3 HW	9,940				940														3,880			720		640	
FL1																									
FL2	16,185																								
FL3																									
GPB LW	55,240		6,600	4,800	8,880	8,760	9,480			8,280	3,360	2,500	840	6,120		5,640	3,740	6,480	9,760	2,520		1,520	10,900	19,560	
GPB HW	11,920		1,040	3,040	2,440	2,820	1,670			2,830	5,240	4,240	5,160	5,560		1,920	5,070	4,110		3,110		5,910	160		
GPB2	1,010																		700						
HID	12,036		2,498	2,938	1,746	2,848	1,642	2,938		2,742	2,108	1,670	4,302	2,198	2,298	4,176	2,396	1,578	3,612	2,462		5,648	2,856	3,712	
PALOOK	10,710		585		520	195	585				495	390	390	390		390	390	390		780			1,055	390	
GRAND TOTAL	271,451	420	62,863	61,518	68,516	66,533	52,577	2,938	41,490	64,632	65,343	69,780	76,312	71,928	41,258	60,056	91,646	47,874	73,032	70,552	42,410	61,018	65,371	102,712	29,130
TOTAL PALLET	229	1	60	44	43	44	33	17	20	48	48	37	60	53	44	79	60	28	57	38	17	71	43	58	11

Table 6.1. The detail of product in-out per day in March 2014…(continued)

TYPE	SHIPPED (March 2014)																	
	1	4	5	6	7	8	11	12	13	14	18	19	20	21	24	25	26	27
PREMIER LW		11,880		136,000			3,960	113,790				125,630					134,380	
PREMIER HW				12,480				35,840	2,080			28,440					16,480	
LED	420	15,060	900	49,990	7,450	500	4,710	28,500	41,180	9,500	35,790	-10,884	26,760	33,450	17,050	22,690	20,350	51,550
LCS3 LW				14,400	700			43,200	2,800			66,240					60,760	150
LCS3 HW				500	500						1,000		600				720	2,800
FL1																		
FL2			2,250															
FL3																		
GPB LW		360		13,800						18,240	7,440							80,960
GPB HW		840		3,000														47,760
GPB2													700					
HID		240		11,960				12,836	14	468		14,012	528	1,500			14,754	
PALOOK				1,715														
GRAND TOTAL		28,380	3,150	243,845	8,650	500	8,670	234,166	46,074	28,208	44,230	223,438	28,588	34,950	17,050	22,690	247,444	183,220
TOTAL PALLET	1	12	2	181	5	1	3	187	11	13	16	197	16	14	6	10	205	109

First Stage. We finally collect 4 criteria and 16 sub-criteria according to the literature and decision makers' knowledge (see table 6.2). We consider 5 alternatives among industrial trucks to be evaluated under the criteria namely IC counter balanced, E-counter balanced, pallet truck, reach truck, and order picker. The problem is constructed into hierarchy as shown in figure 6.2. The problem aims to find out an appropriate industrial truck used for loading, unloading and transporting product to storage rack and shipping area. The evaluation and judgment of alternatives will be performed by 3 decision makers from warehouse representatives; they are 2 supervisors and a senior operator.

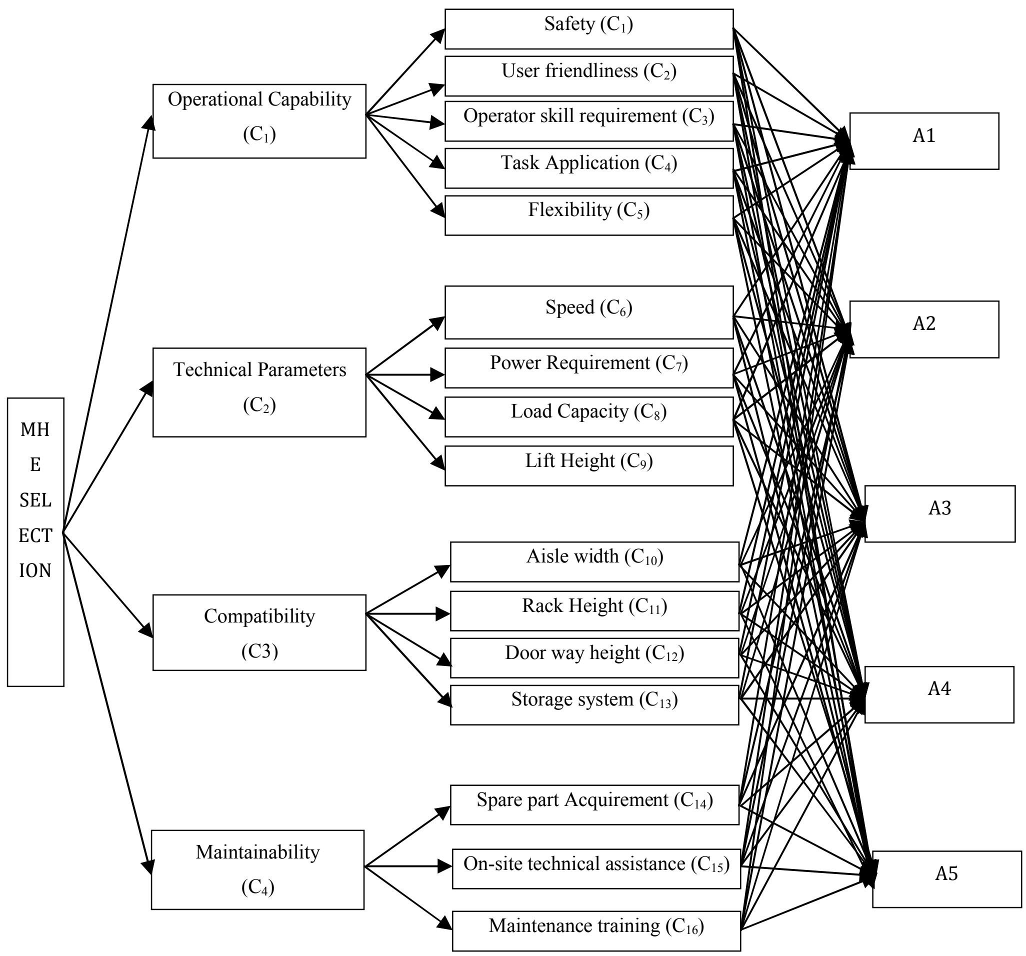

Figure 6.3 Hierarchy of MHE selection problem

Table 6.2 Criteria and sub-criteria definition

Criteria	Consideration	Sub-Criteria	Consideration
Operational Capability (C_1)	Superiority of MHE to give value to the operator, material and task itself when it is being operated	Safety (c_1)	HME can provide safety for operator, material, and environment during the operation
		User friendliness (c_2)	Operator is possible to feel comfortable during operation as well as in case of handling maximum load and long distance travel
		Operator skill requirement (c_3)	MHE should require complexity and skill as less as possible to avoid the difficulty of operation
		Task Application (c_4)	MHE can be used for multi-tasks or operations such as loading, unloading, transporting, stacking and picking
		Flexibility (c_5)	MHE can handle the load in different sizes and weights
Technical Parameters (C_2)	Appropriate features which is offered by MHE to incorporate the operations in terms of material handling	Speed (c_6)	MHE can run in low, medium, or high speed
		Power Requirement (c_7)	MHE consumes power source from Gasoline, LPG or Diesel, or non-powered. The one spending less energy or power and time preparation will be considered.
		Load Capacity (c_8)	MHE can handle a low, medium, or high load capacity
		Lift Height (c_9)	MHE is used for operation in low or high level lifting
Compatibility (C_3)	MHE is likely appropriate with the physical warehouse facility	Aisle width (c_{10})	MHE should be compatible with aisle width so that it can move conveniently
		Rack Height (c_{11})	MHE should be able to load, unload or pick material from/to the rack up to the highest rack's level.
		Door way height (c_{12})	MHE can pass through in-out the door way well with or without load
		Storage system (c_{13})	MHE should be compatible with the storage system as well as rack/palleting
Maintainability (C_4)	the ease of MHE to be maintained in order to repair, prevent unexpected breakdowns etc.	Spare part Acquirement (c_{14})	Spare part should be easy to be acquired such from supplier or market (dealer) when preventive maintenance or break-down should be done.
		On-site technical assistance (c_{15})	The dealer should be able to provide on-site technical assistance if MHE is rent or bought from it
		Maintenance training (c_{16})	An appropriate maintenance training program of the MHE can be established for maintenance operator or technician

Details regarding alternatives' specification are written in the following:

- **A1 (IC Counter balanced Trucks)**

Table 6.3 The details of IC Counter balanced Trucks specification

Specifications	**Units**
Load capacity	1500 kg
Speed	21 km/h
Dimension:	
Lift height (h)	3.035 m
Overall length (l_1)	3.160 m
Length to face of forks (l_2)	2.090 m
Fork length (l_6)	1.070 m
Overall width (b)	0.945 m
Track width (b_{12})	0.795 m
Height of cabin (H)	2.035 m
Turning radius (Wa)	1.720 m
Load distance, center of drive axle to fork	0.400 m
Energy source	Fuel

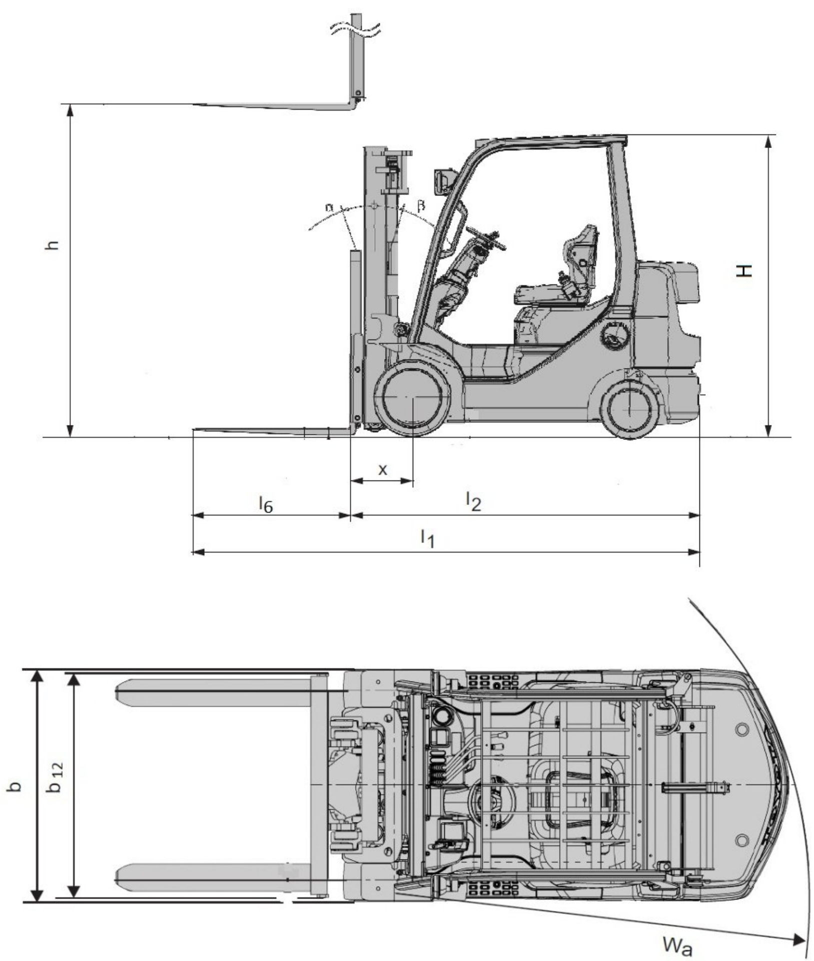

Figure 6.4 IC Counter balanced Trucks dimensions

- **A2 (E Counterbalance)**

Table 6.4 The details of E Counter balanced Trucks specification

Specifications	Units
Load capacity	1000 kg
Speed	20 km/h
Dimension:	
Lift height (h)	3.310 m
Overall length (l_1)	2.365 m
Length to face of forks (l_2)	1.565 m
Fork length (l_6)	0.800 m
Overall width (b)	0.990 m
Track width (b_{12})	0.835 m
Height of cabin (H)	2.055 m
Turning radius (Wa)	1.230 m
Load distance, centre of drive axle to fork (x)	0.330 m
Energy source	Battery (5.1 kW drive motor rating)

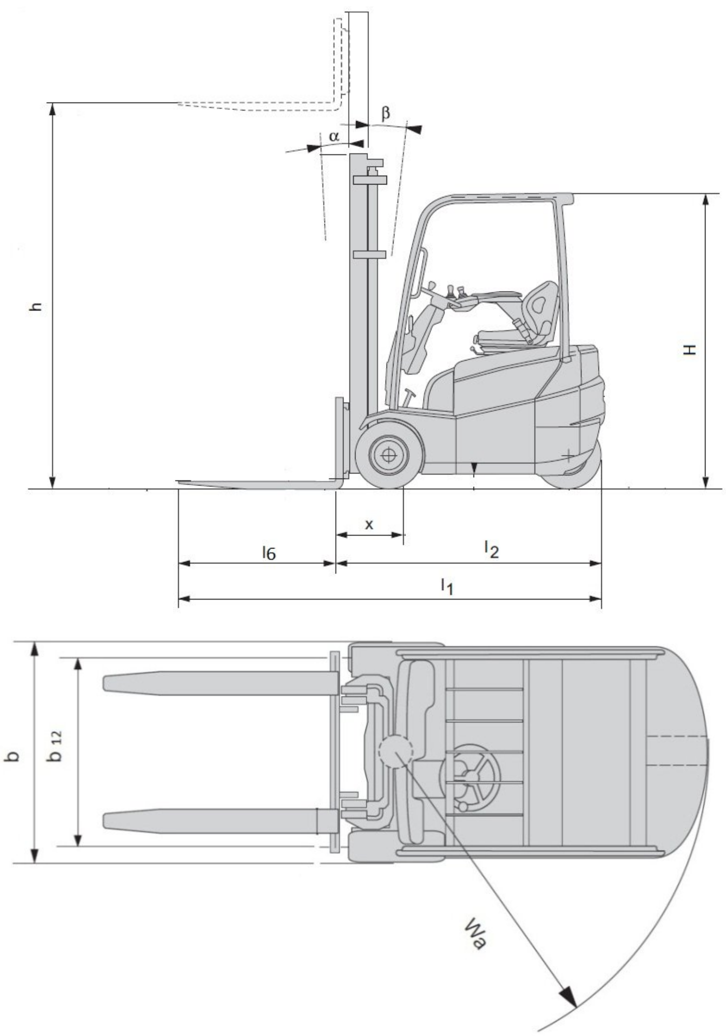

Figure 6.5 E Counter balanced Trucks dimensions

- **A3 (Pallet Truck)**

Table 6.5 The details of pallet trucks specification

Specifications	Units
Load capacity	2000 kg
Speed	19 km/h
Dimension:	
Lift height (h)	0.235 m
Overall length (l_1)	2.024 m
Length to face of forks (l_2)	0.874 m
Fork length (l_6)	1.150 m
Overall width (b)	0.770 m
Track width (b_{12})	0.550 m
Height of cabin (H)	0.880 m
Turning radius (Wa)	1.855 m
Load distance, centre of drive axle to fork (x)	0.958 m
Energy source	Battery (2.2 kW drive motor rating)

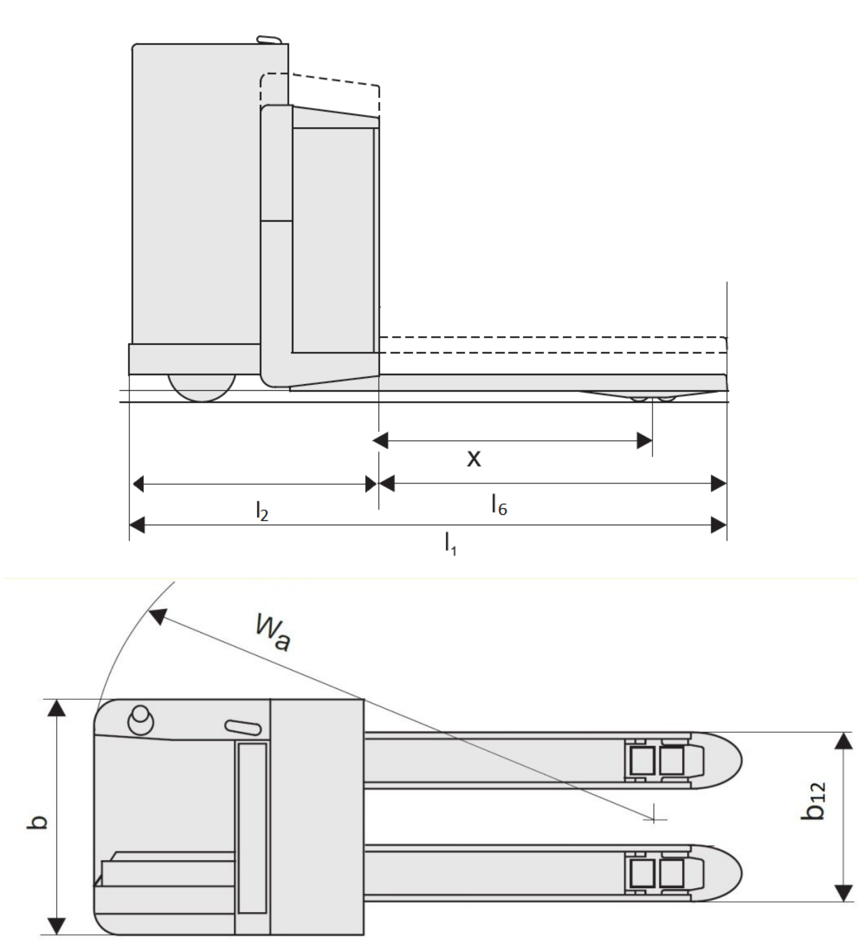

Figure 6.6 Pallet trucks dimensions

- **A4 (Reach Truck)**

Table 6.6 The details of reach trucks specification

Specifications	Units
Load capacity	1400 kg
Speed	14 km/h
Dimension:	
Lift height (h)	4.400 m
Length to face of forks (l_2)	0.874 m
Fork length (l_6)	1.150 m
Overall width (b)	1.120 m
Track width (b_{12})	0.550 m
Overall Height (H)	2.057 m
Turning radius (Wa)	1.649 m
Load distance, center of drive axle to fork (x)	0.418 m
Energy source	Battery (7.5 kW drive motor rating)

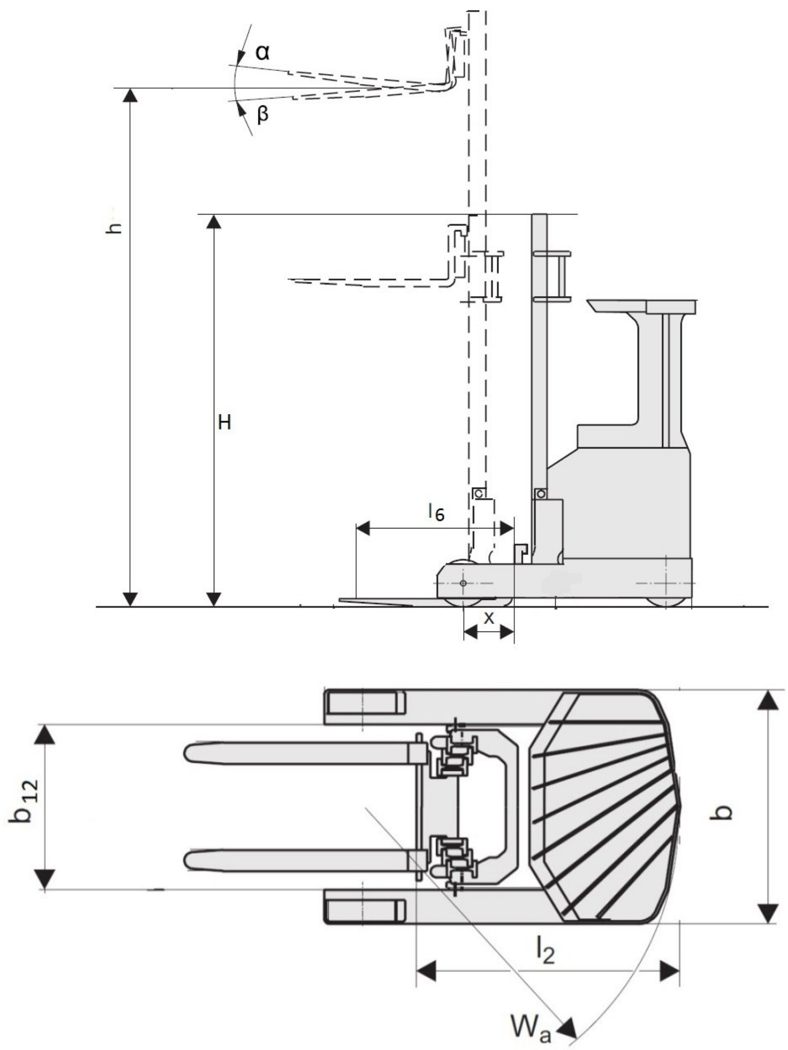

Figure 6.7 Reach trucks dimensions

- **A5 (Order Picker)**

Table 6.7 The details of order picker specification

Specifications	Units
Load capacity	1000 kg
Speed	12 km/h
Dimension:	
Lift height (h)	4.760 m
Overall length (l_1)	2.670 m
Length to face of forks (l_2)	1.770 m
Fork length (l_6)	0.900 m
Overall width (b)	1.000 m
Track width (b_{12})	0.850 m
Height (H)	2.65 m
Turning radius (Wa)	1.660 m
Load distance, center of drive axle to fork (x)	0.225 m
Energy source	Battery (7.5 kW drive motor rating)

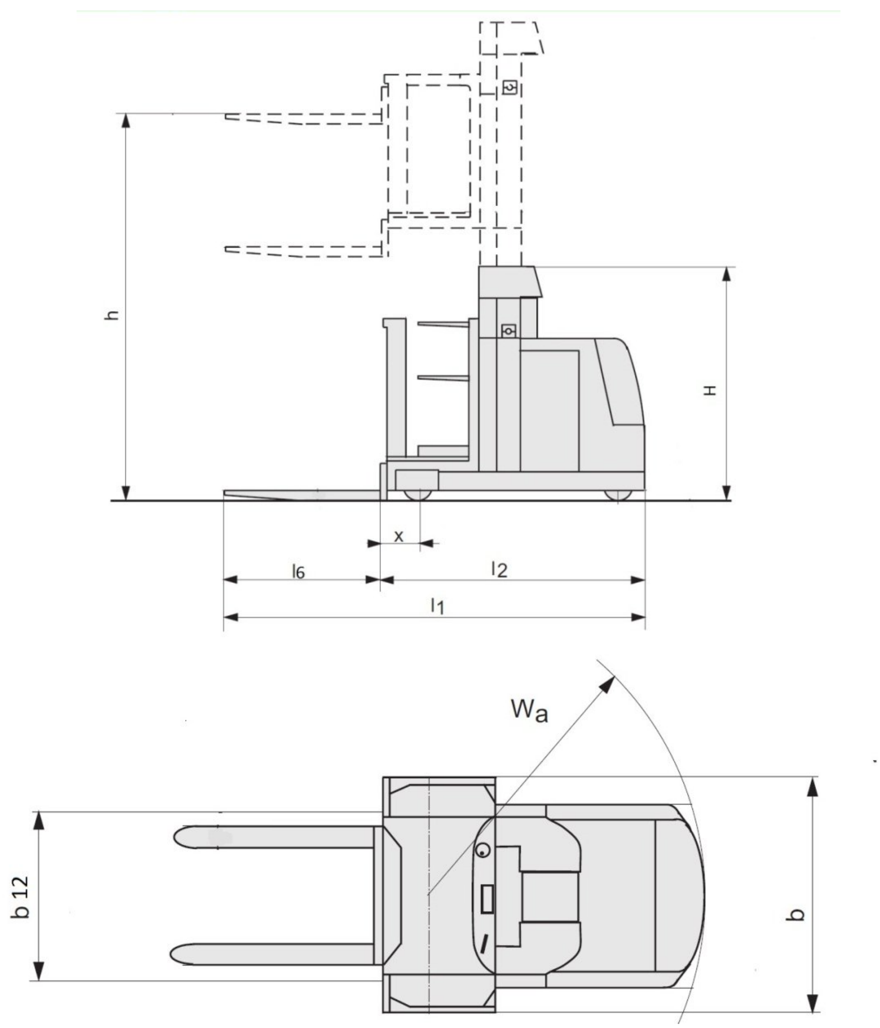

Figure 6.8 order picker dimensions

The initial step before evaluating the alternative is determine the weight of criteria and sub-criteria. The weight of criteria and sub-criteria are derived by using AHP. The calculation can be systematically done through the following steps:

1) Construct pair-wise comparison matrix for evaluation criteria & sub-criteria by using Saaty's scale judged by decision makers (see Appendix A.1). The pair-wise comparison matrices for criteria judged by DMs are shown in table 6.8.

Table 6.8 Pair-wise comparison matrices for criteria

DM 1	Operational Capability	Technical Parameters	Compatibility	Maintainability
Operational Capability	1	5	1	3
Technical Parameters	0.2	1	0.25	0.333
Compatibility	1	4	1	3
Maintainability	0.333	3	0.333	1
DM 2	**Operational Capability**	**Technical Parameters**	**Compatibility**	**maintainability**
Operational Capability	1	5	2	3
Technical Parameters	0.2	1	0.333333333	0.5
Compatibility	0.5	3	1	2
Maintainability	0.333333333	2	0.5	1
DM 3	**Operational Capability**	**Technical Parameters**	**Compatibility**	**maintainability**
Operational Capability	1	3	0.333333333	4
Technical Parameters	0.333333333	1	0.2	3
Compatibility	3	5	1	7
Maintainability	0.25	0.333333333	0.142857143	1

2) Calculate CR in order to perform consistency test.

Calculate column sum (a_{ij}) for each column as shown in table 6.9 bellow.

Table 6.9 Total element column of pair-wise comparison matrix for criteria judged by DM 1

DM 1	Operational Capability	Technical Parameters	Compatibility	Maintainability
Operational Capability	1	5	1	3
Technical Parameters	0.2	1	0.25	0.333
Compatibility	1	4	1	3
Maintenability	0.333	3	0.333	1
TOTAL	2.533	13	2.583	7.333

Normalize each cell ($x_{ij} = a_{ij}/\sum a_{ij}$) as shown in table 6.10.

Table 6.10. Normalized pair-wise comparison matrix for criteria judged by DM 1

DM 1	Operational Capability	Technical Parameters	Compatibility	Maintainability
Operational Capability	0.3947	0.3846	0.3871	0.4091
Technical Parameters	0.0789	0.0769	0.0968	0.0455
Compatibility	0.3947	0.3077	0.3871	0.4091
Maintenability	0.1316	0.2308	0.1290	0.1364

Calculate weight ($W_i = \sum x_{ij}/n$) which is shown in table 6.11.

Table 6.11. Weight of criteria judged by DM 1

DM 1	Operational Capability	Technical Parameters	Compatibility	Maintainability	W
Operational Capability	0.3947	0.3846	0.3871	0.4091	0.3939
Technical Parameters	0.0789	0.0769	0.0968	0.0455	0.0745
Compatibility	0.3947	0.3077	0.3871	0.4091	0.3747
Maintenability	0.1316	0.2308	0.1290	0.1364	0.1569

Then by using equation (4.3), and (4.4), CI and CR can be calculated as follows:

$CI = \frac{4.0672-4}{4-1} = 0.0224$ and $CR = \frac{0.0244}{0.9} = 0.02490 \leq 0.1$

where RI = 0.9 (see table 4.2)

CR is less than 0.1, thus, the pair-wise comparison matrix satisfies consistency test which means there is no randomness from decision maker in conveying opinion. The consistency test for all sub-criteria judged by each DM can be seen in Appendix A.2.

3) Transform pairwise comparison matrix into TFN as shown in table 6.12. For overall matrices, they are shown in appendix A.3.

Table 6.12.Fuzzy pairwise comparison matrices for criteria

DM 1	Operational Capability	Technical Parameters	Compatibility	Maintainability
Operational Capability	(1,1,1)	(3,5,7)	(1,1,1)	(1,3,5)
Technical Parameters	(1/7,1/5,1/3)	(1,1,1)	(1/6,1/4,1/2)	(1/5,1/3,1)
Compatibility	(1,1,1)	(2,4,6)	(1,1,1)	(1,3,5)
Maintainability	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1,1,1)

DM 2	Operational Capability	Technical Parameters	Compatibility	Maintainability
Operational Capability	(1,1,1)	(3,5,7)	(1,2,3)	(1,3,5)
Technical Parameters	(1/7,1/5,1/3)	(1,1,1)	(1/5,1/3,1)	(1/3,1/2,1)
Compatibility	(1/3,1/2,1)	(1,3,5)	(1,1,1)	(1,2,3)
Maintainability	(1/5,1/3,1)	(1,2,3)	(1/3,1/2,1)	(1,1,1)
DM 3	Operational Capability	Technical Parameters	Compatibility	Maintainability
Operational Capability	(1,1,1)	(1,3,5)	(1/5,1/3,1)	(2,4,6)
Technical Parameters	(1/5,1/3,1)	(1,1,1)	(1/7,1/5,1/3)	(1,3,5)
Compatibility	(1,3,5)	(3,5,7)	(1,1,1)	(5,7,9)
Maintainability	(1/4,1/4,1/2)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1,1,1)

4) For each element of fuzzy pair-wise comparison matrix for criteria ($\tilde{a}_{ij}$) and sub-criteria ($\tilde{a}_{lj}$), use geometric mean to aggregate decision makers' judgment according to equation (4.5) so that a single value incorporating decision makers' opinion entirely will be obtained such shown in table 6.13. The aggregated matrices entirely can be seen in appendix A.4.

Table 6.13. aggregated fuzzy pair-wise comparison matrix for criteria

	Operational Capability	Technical Parameters	Compatibility	Maintainability
Operational	(1,1,1)	(2.080, 4.217, 6.257)	(0.585, 0.874, 1.442)	(1.260, 3.302, 5.313)
Technical	(0.160, 0.237, 0.481)	(1,1,1)	(0.168, 0.255, 0.550)	(0.405, 0.794, 1.710)
Compatibility	(0.693, 1.145, 1.710)	(1.817, 3.915, 5.944)	(1,1,1)	(1.710, 3.476, 5.130)
Maintainability	(0.215, 0.303, 0.794)	(0.585, 1.260, 2.466)	(0.195, 0.288, 0.585)	(1,1,1)

for an example,

$\tilde{a}_{12} = ((3,5,7) \otimes (3,5,7) \otimes (1,3,5))^{1/3}$

$= ((3x3x1)^{1/3}, (5x5x3)^{1/3}, (7x7x5)^{1/3})) = (2.080, 4.217, 6.257)$

5) Calculate fuzzy weight for each criterion ($\tilde{w}_i$) and sub-criterion ($\tilde{w}_l$) by using equation (4.6). The results are summarized in table 6.14.

for example,

$\tilde{r}_i = (\tilde{a}_{i1} \otimes \ldots \otimes \tilde{a}_{ij} \otimes \ldots \otimes \tilde{a}_{in})^{1/n}$

$\tilde{r}_1 = (\tilde{a}_{11} \otimes \tilde{a}_{12} \otimes \tilde{a}_{13} \otimes \tilde{a}_{14})^{1/4}$

$= ((1,1,1) \otimes (2.080, 4.217, 6.257) \otimes (0.585, 0.874, 1.442) \otimes (1.260, 3.302, 5.313))^{1/4}$

$= (1x2.080x0.585x1.260)^{1/4},(1x4.217x0.874)x3.302)^{1/4}, (1x6.257x1.442x5.313)^{1/4}$

$= (1.113, 1.868, 2.631)$

$\tilde{r}_2$ =($\tilde{a}_{21} \otimes \tilde{a}_{22} \otimes \tilde{a}_{23} \otimes \tilde{a}_{24})^{1/4}$

= ((0.160, 0.237, 0.481)⊗(1,1,1)⊗(0.168, 0.255, 0.550)⊗(0.405, 0.794, 1.710))$^{1/4}$

= (0.160x1x0.168x0.405)$^{1/4}$,(0.237x1x0.255x0.794)$^{1/4}$, (0.481x1x0.550x1.710)$^{1/4}$

= (0.323, 0.468, 0.820)

$\tilde{r}_3$ =($\tilde{a}_{31} \otimes \tilde{a}_{32} \otimes \tilde{a}_{33} \otimes \tilde{a}_{34})^{1/4}$

= ((0.693, 1.145, 1.710)⊗(1.817, 3.915, 5.944)⊗(1,1,1)⊗(1.710, 3.476,5.130))$^{1/4}$

= (0.693x1.817x1x1.710)$^{1/4}$,(1.145x3.915x1x3.476)$^{1/4}$, (1.710x5.944x1x5.130)$^{1/4}$

= (1.212, 1.987, 2.687)

$\tilde{r}_4$ =($\tilde{a}_{41} \otimes \tilde{a}_{42} \otimes \tilde{a}_{43} \otimes \tilde{a}_{44})^{1/4}$

= ((0.215, 0.303, 0.794)⊗(0.585, 1.260, 2.466)⊗(0.195, 0.288,0.585)⊗(1, 1,1))$^{1/4}$

= (0.215x0.585x0.195x1)$^{1/4}$,(0.303 x1.260 x0.288x1)$^{1/4}$, (0.794x2.466 x0.585x1)$^{1/4}$

= (0.396, 0.576, 1.034)

Table 6.14. Fuzzy weight of criteria and sub-criteria

Criteria	Fuzzy weight ($\tilde{w}_i$)	Sub-criteria	Fuzzy weight ($\tilde{w}_l$)
Operational Capability (C_1)	(0.155, 0.381, 0.865)	Safety (c_1)	(0.169, 0.449, 1.072)
		User friendliness (c_2)	(0.097, 0.222, 0.585)
		Operator skill requirement (c_3)	(0.025, 0.049, 0.128)
		Task Application (c_4)	(0.072, 0.169, 0.459)
		Flexibility (c_5)	(0.024, 0.112, 0.336)
Technical Parameters (C_2)	(0.045, 0.096, 0.269)	Speed (c_6)	(0.031, 0.055, 0.128)
		Power Requirement (c_7)	(0.056, 0.123, 0.317)
		Load Capacity (c_8)	(0.159, 0.352, 0.769)
		Lift Height (c_9)	(0.219, 0.470, 0.934)
Compatibility (C_3)	(0.169, 0.406, 0.883)	Aisle width (c_{10})	(0.083, 0.192, 0.463)
		Rack Height (c_{11})	(0.079, 0.171, 0.401)
		Door way height (c_{12})	(0.032, 0.060, 0.176)
		Storage system (c_{13})	(0.263, 0.577, 1.149)
Maintainability (C_4)	(0.055, 0.118, 0.340)	Spare part Acquirement (c_{14})	(0.207, 0.467, 1.009)
		On-site technical assistance (c_{15})	(0.064, 0.117, 0.330)
		Maintenance training (c_{16})	(0.194, 0.416, 0.813)

$\widetilde{w}_i = \tilde{r}_i \oslash [\tilde{r}_1 \oplus \ldots \oplus \tilde{r}_i \oplus \ldots \oplus \tilde{r}_n]$

$\widetilde{w}_1 = \tilde{r}_1 \oslash [\tilde{r}_1 \oplus \tilde{r}_2 \oplus \tilde{r}_3 \oplus \tilde{r}_4]$

= (1.113, 1.868, 2.631) ⊘ [(1.113+0.323+1.212+0.396), (1.868+0.468+1.987+0.576), (2.631+0.820+2.687+1.034)]

= (1.113, 1.868, 2.631) ⊘ [3.043, 4.898, 7.173]

= (0.155, 0.381, 0.865)

6) Obtain crisp value of criteria weight (w_i) and sub-criteria weight (w_l) by using COG method (eq. 4.7). The crisp weight of criteria and sub-criteria are summarized in table 6.15.

Table 6.15. Crisp weight of criteria sub-criteria

Criteria	weight (w_i)	Sub-criteria	weight (w_l)
Operational Capability (C_1)	0.467	Safety (c_1)	0.564
		User friendliness (c_2)	0.301
		Operator skill requirement (c_3)	0.067
		Task Application (c_4)	0.233
		Flexibility (c_5)	0.157
Technical Parameters (C_2)	0.137	Speed (c_6)	0.071
		Power Requirement (c_7)	0.165
		Load Capacity (c_8)	0.427
		Lift Height (c_9)	0.541
Compatibility (C_3)	0.486	Aisle width (c_{10})	0.246
		Rack Height (c_{11})	0.217
		Door way height (c_{12})	0.089
		Storage system (c_{13})	0.663
Maintainability (C_4)	0.171	Spare part Acquirement (c_{14})	0.561
		On-site technical assistance (c_{15})	0.170
		Maintenance training (c_{16})	0.474

For an example,

$$Z^*_{\text{Operational Capability}(0.155,\,0.381,\,0.865)} = \frac{\int_{0.155}^{0.381} \frac{(x-0.381)x\,dx}{(0.381-0.155)} + \int_{0.381}^{0.865} \frac{(0.865-x)x\,dx}{(0.865-0.381)}}{\int_{0.155}^{0.381} \frac{(x-0.381)\,dx}{(0.381-0.155)} + \int_{0.381}^{0.865} \frac{(0.865-x)\,dx}{(0.865-0.381)}}$$

= (0.035+ 0.131)/(0.113+0.242) = 0.467

7) Calculate global weight of sub-criteria (W_j) using equation (4.8). Table 6.16 shows global weight of sub-criteria.

For example,

W_1 = 0.467 x 0.564 = 0.263

W_2 = 0.467 x 0.301= 0.141

W_3 = 0.467 x 0.067= 0.031

W_4 = 0.467 x 0.233= 0.109

W_5 = 0.467 x 0.157= 0.073

Table 6.16. Global weight of sub-criteria

Sub-criteria	weight (W)	Priority
Safety (c_1)	0.263	2
User friendliness (c_2)	0.141	3
Operator skill requirement (c_3)	0.031	13
Task Application (c_4)	0.109	5
Flexibility (c_5)	0.073	11
Speed (c_6)	0.010	16
Power Requirement (c_7)	0.023	15
Load Capacity (c_8)	0.058	10
Lift Height (c_9)	0.074	9
Aisle width (c_{10})	0.120	4
Rack Height (c_{11})	0.105	6
Door way height (c_{12})	0.043	12
Storage system (c_{13})	0.322	1
Spare part Acquirement (c_{14})	0.096	7
On-site technical assistance (c_{15})	0.029	14
Maintenance training (c_{16})	0.081	8

In this case, we utilize integration of objective and subjective weight for particular sub-criteria. Generally, industrial truck can work in a range of speed, load capacity, and lift height. Because each alternative may run in several modes either its speed, load capacity, and lift height which are measurable, entropy method is proposed in order to determine the objective weight of criteria particularly for speed, load capacity, and lift height,. By referring to the literature in one of industrial truck manufacturers, we collect some information in terms of industrial trucks performance details which are shown in table 6.17.

Table 6.17. Operating speed, load capacity & lift height of each alternative

Speed (km/h)	A1 (IC Counter balanced Trucks)	A2 (E-counterbalanced Trucks)	A3 (Pallet Truck)	A4 (Reach Trucks)	A5 (Order Picker)
1	17	12	8.5	8	9
2	17.5	13.5	12	11	9.5
3	18	14	15.1	11.2	11
4	19	16	19	12	11.5
5	21	20	19.9	14	12
Load Capacity (kg)	**A1 (IC Counter balanced Trucks)**	**A2 (E-counterbalanced Trucks)**	**A3 (Pallet Truck)**	**A4 (Reach Trucks)**	**A5 (Order Picker)**
1	1500	1000	1300	1200	1000
2	3500	1500	2000	1400	1200
3	5000	2000	2500	1600	1400
4	7000	6000	2400	2500	1800
5	8000	8500	3000	2700	2500
Lift Height (m)	**A1 (IC Counter balanced Trucks)**	**A2 (E-counterbalanced Trucks)**	**A3 (Pallet Truck)**	**A4 (Reach Trucks)**	**A5 (Order Picker)**
1	6	6	0.71	7.5	2.8
2	7	6.5	0.8	8.5	6.3
3	8	7.5	1.6	12.5	12

We use the information above to determine its objective weight. The calculation can be systematically done through these steps:

1) Compute TFN of evaluation criteria under each alternative by using equation (4.9). The TFN of speed, load capacity & lift height can be seen in table 6.18.

For an example,

Load capacity-A1:

$l = \min \{1500, 3500, 5000, 7000, 8000\} = 1500$

$m = \sqrt[5]{1500 + 3500 + 5000 + 7000 + 8000} = 4300$

$u = \max \{1500, 3500, 5000, 7000, 8000\} = 8000$

Table 6.18. TFN of objective c_6, c_8 & c_9

Criteria	A1	A2	A3	A4	A5
Speed (km/h)	(17, 18.4, 21)	(12, 14.9, 20)	(8.5, 14.2,19.9)	(8, 11.1, 14)	(9, 10.5, 12)
Load Capacity (kg)	(1500, 4300.0, 8000)	(1000, 2734.9, 8500)	(1300, 2158.0, 3000)	(1200, 1785.4, 2700)	(1000, 1498.7, 2500)
Lift Height (m)	(6, 7, 8)	(6, 6.6, 7.5)	(0.71, 0.97, 1.6)	(7.5, 9.3, 12.5)	(2.8, 6.0, 12)

2) Obtain crisp value of fuzzy evaluation criteria according to COG method. The results are shown in table 6.19.

Table 6.19 crisp value of objective c_6, c_8 & c_9

Criteria	A1	A2	A3	A4	A5
Speed (km/h)	18.81	15.62	14.21	11.02	10.51
Load Capacity (kg)	4599.98	2622.26	2152.66	1895.15	1666.22
Lift Height (m)	7.0	6.7	1.09	9.76	6.92

3) Calculate the normalized crisp value of evaluation criteria under each alternative. All criteria are about positive implication to the operating performance. So, the normalization is computed by dividing each value with the max value. The results are summarized in table 6.20.

Table 6.20 Normalized crisp value of objective c_6, c_8 & c_9

Criteria	A1	A2	A3	A4	A5	TOTAL
Speed (km/h)	1	0.830	0.755	0.586	0.559	3.730
Load Capacity (kg)	1	0.570	0.468	0.412	0.362	2.812
Lift Height (m)	0.716	0.688	0.112	1	0.709	2.225

4) Calculate the entropy value by using equation (4.10)

$$E_1 = -\frac{1}{\ln 5}\left[\left(\frac{1}{3.730}\ln\frac{1}{3.730}\right)+\left(\frac{0.830}{3.730}\ln\frac{0.830}{3.730}\right)+\left(\frac{0.755}{3.730}\ln\frac{0.755}{3.730}\right)+\left(\frac{0.586}{3.730}\ln\frac{0.586}{3.730}\right)+\left(\frac{0.559}{3.730}\ln\frac{0.559}{3.730}\right)\right]$$

= 0.9853

$$E_2 = -\frac{1}{\ln 5}\left[\left(\frac{1}{2.812}\ln\frac{1}{2.812}\right)+\left(\frac{0.570}{2.812}\ln\frac{0.570}{2.812}\right)+\left(\frac{0.468}{2.812}\ln\frac{0.468}{2.812}\right)+\left(\frac{0.412}{2.812}\ln\frac{0.412}{2.812}\right)+\left(\frac{0.362}{2.812}\ln\frac{0.362}{2.812}\right)\right]$$

= 0.9537

$$E_3 = -\frac{1}{\ln 5}\left[\left(\frac{0.716}{2.225}\ln\frac{0.716}{2.225}\right)+\left(\frac{0.688}{2.225}\ln\frac{0.688}{2.225}\right)+\left(\frac{0.112}{2.225}\ln\frac{0.112}{2.225}\right)+\left(\frac{1}{2.225}\ln\frac{1}{2.225}\right)+\left(\frac{0.709}{2.225}\ln\frac{0.709}{2.225}\right)\right]$$

= 0.9955

5) Calculate the degree of diversification from entropy value

d_1 = 1- E_1 = 1-0.9853 = 0.0147

d_2 = 1- E_2 = 1-0.9537= 0.0463

d_3 = 1- E_3 = 1-0.9955= 0.0045

6) Obtain objective weight by using equation (4.12)

$$w_{o1} = \frac{0.0147}{0.0147+0.0463+0.0045} = 0.224$$

$$w_{o2} = \frac{0.0463}{0.0147+0.0463+0.0045} = 0.707$$

$$w_{o3} = \frac{0.0045}{0.0147+0.0463+0.0045} = 0.069$$

$$0 \le w_{oj} \le 1;\ \sum_{i=1}^{n} w_{oj} = 1$$

Finally, the objective weight of particular criteria has been derived. Then, we would like to integrate objective weight and subjective weight derived from Fuzzy AHP in the 6.16. Initially, criterion and weight of speed, load capacity and lift height are denoted by c_6, c_8, c_9 and W_6, W_8, W_9. By using equation (4.13), integrated weights are calculated in the following:

$$W_6 = \frac{0.010x\ 0.244}{(0.010x0.244)+(0.058x0.707)+(0.074x0.069)}\ x(0.010 + 0.058 + 0.074)$$

= 0.007

$$W_8 = \frac{0.058x0.707}{(0.010x0.244)+(0.058x0.707)+(0.074x0.069)}\ x(0.010 + 0.058 + 0.074)$$

$= 0.140$

$$W_9 = \frac{0.074x0.069}{(0.010x0.244)+(0.058x0.707)+(0.074x0.069)}\,x(0.010 + 0.058 + 0.074)$$

$= 0.017$

Regarding alternative evaluation, overall weight of alternative will be determined through fuzzy TOPSIS according to the weight of evaluation criteria shown in table 6.21. It shows the upgraded weight after integration particularly for c_6, c_8, c_9.

Table 6.21. Integrated weight of sub-criteria

Sub-criteria	weight (W)	Priority
Safety (c_1)	0.263	2
User friendliness (c_2)	0.141	3
Operator skill requirement (c_3)	0.031	12
Task Application (c_4)	0.109	6
Flexibility (c_5)	0.073	10
Speed (c_6)	0.007	16
Power Requirement (c_7)	0.023	14
Load Capacity (c_8)	0.140	4
Lift Height (c_9)	0.017	15
Aisle width (c_{10})	0.120	5
Rack Height (c_{11})	0.105	7
Door way height (c_{12})	0.043	11
Storage system (c_{13})	0.322	1
Spare part Acquirement (c_{14})	0.096	8
On-site technical assistance (c_{15})	0.029	13
Maintenance training (c_{16})	0.081	9

This following session covers the use of fuzzy TOPSIS in order to evaluate the alternative and find the best one. Alternative will be judged by 3 decision makers by using linguistic rating shown in table 6.22. The decision makers' opinion about the alternatives is summarized in table 6.23.

Table 6.22. Linguistic variables for the importance weight of the criteria

Linguistic Variable	Corresponding TFN
Very Poor (VP)	(0, 0, 1)
Poor (P)	(0, 1, 3)
Medium Poor (MP)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Medium Good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very Good (VG)	(9, 10, 10)

Table 6.23 Decision makers' judgment about alternatives

Criteria	DM 1					DM 2					DM 3				
	A_1	A_2	A_3	A_4	A_5	A_1	A_2	A_3	A_4	A_5	A_1	A_2	A_3	A_4	A_5
c_1	MP	F	VG	F	MG	F	F	G	MG	F	MP	MG	VG	F	MG
c_2	G	MG	MP	F	G	MG	G	MP	G	MG	MG	MG	F	G	MG
c_3	F	MP	VG	MG	MG	F	F	G	F	G	MP	MP	G	MG	G
c_4	MG	G	F	F	MG	G	MG	F	G	F	G	G	F	VG	F
c_5	G	MG	F	VG	F	G	MG	MG	VG	F	G	G	MG	MG	F
c_6	Objective rating					Objective rating					Objective rating				
c_7	G	F	F	F	F	MG	MP	MP	MP	MP	G	F	F	F	F
c_8	Objective rating					Objective rating					Objective rating				
c_9	Objective rating					Objective rating					Objective rating				
c_{10}	F	F	G	MP	MG	F	MP	G	MP	G	F	F	MG	MP	MG
c_{11}	MG	F	MP	MG	F	MG	MG	MP	MG	MG	MG	F	MP	MG	MG
c_{12}	MG	MG	G	MG	MG	MG	MG	G	MG	MG	F	F	MG	F	F
c_{13}	G	G	MP	G	G	MG	MG	F	MG	MG	G	G	MP	G	G
c_{14}	F	F	F	F	MG	F	MG	MG	F	MG	MG	F	F	F	F
c_{15}	F	MG	MG	F	MG	F	F	F	MP	MG	MP	F	F	F	MG
c_{16}	MP	F	MG	MP	F	MP	F	F	MP	MG	MP	MP	MG	MP	F

According to the fuzzy TOPSIS, the alternative ranking can be found out through the following steps:

1) Aggregate TFN of decision makers' opinion regarding alternatives evaluation by using equation (4.14). The result is shown in table 6.24.

Table 6.24. Aggregated alternative rating

Criteria	A_1	A_2	A_3	A_4	A_5
c_1	(1.667, 3.667, 5.667)	(3.667, 5.667, 7.667)	(8.333, 9.667, 10)	(3.667, 5.667, 7.667)	(4.333, 6.333, 8.333)
c_2	(5.667, 7.667, 9.333)	(5.667, 7.667, 9.333)	(1.667, 3.667, 5.667)	(6.333, 8.333, 9.667)	(5.667, 7.667, 9.333)
c_3	(1.667, 3.667, 5.667)	(1.667, 3.667, 5.667)	(7.667, 9.333, 10)	(3.667, 5.667, 7.667)	(6.333, 8.333, 9.667)
c_4	(6.333, 8.333, 9.667)	(6.333, 8.333, 9.667)	(3, 5, 7)	(8.333, 9.333, 10)	(3.667, 5.667, 7.667)
c_5	(7, 9, 10)	(5.667, 7.667, 9.333)	(4.333, 6.333, 8.333)	(7, 8.667, 9.667)	(3, 3, 7)
c_6	(17, 18.4, 21)	(12, 14.9, 20)	(8.5, 14.2, 19.9)	(8, 11.1, 14)	(9, 10.5, 12)
c_7	(6.333, 8.333, 9.667)	(2.333, 4.333, 6.333)	(2.333, 4.333, 6.333)	(2.333, 4.333, 6.333)	(2.333, 4.333, 6.333)
c_8	(1500, 4300, 8000)	(1000, 2734.9, 8500)	(1300, 2158.0, 3000)	(1200, 1785.4, 2700)	(1000, 1498.7, 2500)
c_9	(6, 7, 8)	(6, 6.6, 7.5)	(0.71, 0.97, 1.6)	(7.5, 9.3, 12.5)	(2.8, 6, 12)
c_{10}	(3, 5, 7)	(2.333, 4.333, 6.333)	(6.333, 8.333, 9.667)	(1, 3, 5)	(5.667, 7.667, 9.333)
c_{11}	(5, 7, 9)	(3.667, 5.667, 7.667)	(1, 3, 5)	(5, 7, 9)	(4.333, 6.333, 8.333)
c_{12}	(4.333, 6.333, 8.333)	(4.333, 6.333, 8.333)	(6.333, 8.333, 9.667)	(4.333, 6.333, 8.333)	(4.333, 6.333, 8.333)
c_{13}	(6.333, 8.333, 9.667)	(6.333, 8.333, 9.667)	(1.667, 3.667, 5.667)	(6.333, 8.333, 9.667)	(6.333, 8.333, 9.667)
c_{14}	(3.667, 5.667, 7.667)	(3.667, 5.667, 7.667)	(3.667, 5.667, 7.667)	(3, 5, 7)	(4.333, 6.333, 8.333)
c_{15}	(2.333, 4.333, 6.333)	(3.667, 5.667, 7.667)	(3.667, 5.667, 7.667)	(2.333, 4.333, 6.333)	(5, 7, 9)
c_{16}	(1, 3, 5)	(2.333, 4.333, 6.333)	(4.333, 6.333, 8.333)	(1, 3, 5)	(3.667, 5.667, 7.667)

2) Normalize fuzzy decision matrix and it can be seen in table 6.25.

Table 6.25. Normalized fuzzy decision matrix

Criteria	A_1	A_2	A_3	A_4	A_5
c_1 0.263	(0.167, 0.367, 0.567)	(0.367, 0.567, 0.76)	(0.833, 0.967 1)	(0.367, 0.567, 0.767)	(0.433, 0.633, 0.833)
c_2 0.141	(0.586, 0.793, 0.966)	(0.586, 0.793, 0.966)	(0.172, 0.379, 0.586)	(0.655, 0.862, 1)	(0.586, 0.793, 0.966)
c_3 0.031	(0.167, 0.367, 0.567)	(0.167, 0.367, 0.567)	(0.767, 0.933, 1)	(0.367, 0.567, 0.767)	(0.633, 0.833, 0.967)
c_4 0.109	(0.633, 0.833, 0.967)	(0.633, 0.833, 0.967)	(0.3, 0.5, 0.7)	(0.833, 0.933, 1)	(0.367, 0.567, 0.767)
c_5 0.073	(0.7, 0.9, 1)	(0.567, 0.767, 0.933)	(0.433, 0.633, 0.833)	(0.7, 0.867, 0.967)	(0.3, 0.5, 0.7)
c_6 0.007	(0.810, 0.878, 1)	(0.571, 0.708, 0.952)	(0.405, 0.677, 0.948)	(0.381, 0.527, 0.667)	(0.429, 0.502, 0.571)

c_7 0.023	(0.655, 0.862, 1)	(0.241, 0.448, 0.655)	(0.241, 0.448, 0.655)	(0.241, 0.448, 0.655)	(0.241, 0.448, 0.655)
c_8 0.140	(0.176, 0.506, 0.941)	(0.118, 0.322, 1)	(0.153, 0.254, 0.353)	(0.141, 0.210, 0.318)	(0.118, 0.176, 0.294)
c_9 0.017	(0.480, 0.556, 0.640)	(0.480, 0.531, 0.6)	(0.057, 0.077, 0.128)	(0.6, 0.742, 1)	(0.224, 0.477, 0.960)
c_{10} 0.120	(0.310, 0.517, 0.724)	(0.241, 0.448, 0.655)	(0.655, 0.862, 1)	(0.103, 0.310, 0.517)	(0.586, 0.793, 0.966)
c_{11} 0.105	(0.556, 0.778, 1)	(0.407, 0.630, 0.852)	(0.111, 0.333, 0.556)	(0.556, 0.778, 1)	(0.481, 0.704, 0.926)
c_{12} 0.043	(0.655, 0.862, 1)	(0.655, 0.862, 1)	(0.172, 0.379, 0.586)	(0.655, 0.862, 1)	(0.655, 0.862, 1)
c_{13} 0.322	(0.655, 0.862, 1)	(0.655, 0.862, 1)	(0.172, 0.379, 0.586)	(0.655, 0.862, 1)	(0.655, 0.862, 1)
c_{14} 0.096	(0.259, 0.481, 0.704)	(0.407, 0.630, 0.852)	(0.407, 0.630, 0.852)	(0.259, 0.481, 0.704)	(0.556, 0.778, 1)
c_{15} 0.029	(0.259, 0.481, 0.704)	(0.407, 0.630, 0.852)	(0.407, 0.630, 0.852)	(0.259, 0.481, 0.704)	(0.556, 0.778, 1)
c_{16} 0.081	(0.120, 0.360, 0.6)	(0.280, 0.520, 0.760)	(0.520, 0.760, 1)	(0.120, 0.360, 0.6)	(0.440, 0.680, 0.920)

3) Calculate weighted normalized fuzzy rating by multiplying with the corresponding criterion weight. Table 6.26 summarizes the result overall.

Table 6.26. Weighted normalized fuzzy rating

A_1	A_2	A_3	A_4	A_5
(0.0439, 0.0965, 0.1492)	(0.0965, 0.1492, 0.2018)	(0.2194, 0.2545, 0.2632)	(0.0965, 0.1492, 0.2018)	(0.1141, 0.1667, 0.2194)
(0.0825, 0.1116, 0.1359)	(0.0825, 0.1116, 0.1359)	(0.0243, 0.0534, 0.0825)	(0.0922, 0.1213, 0.1407)	(0.0825, 0.1116, 0.1359)
(0.0052, 0.0115, 0.0178)	(0.0052, 0.0115, 0.0178)	(0.0241, 0.0294, 0.0315)	(0.0115, 0.0178, 0.0241)	(0.0199, 0.0262, 0.0304)
(0.0689, 0.0907, 0.1052)	(0.0689, 0.0907, 0.1052)	(0.0327, 0.0544, 0.0762)	(0.0907, 0.1016, 0.1089)	(0.0399, 0.0617, 0.0835)
(0.0514, 0.0661, 0.0735)	(0.0416, 0.0563, 0.0686)	(0.0318, 0.0465, 0.0612)	(0.0514, 0.0637, 0.0710)	(0.0220, 0.0367, 0.0514)
(0.0060, 0.0065, 0.0074)	(0.0042, 0.0053, 0.0071)	(0.0030, 0.0050, 0.0070)	(0.0028, 0.0039, 0.0050)	(0.0032, 0.0037, 0.0042)
(0.0148, 0.0195, 0.0226)	(0.0055, 0.0101, 0.0148)	(0.0055, 0.0101, 0.0148)	(0.0055, 0.0101, 0.0148)	(0.0055, 0.0101, 0.0148)
(0.0247, 0.0707, 0.1316)	(0.0165, 0.0450, 0.1398)	(0.0214, 0.0355, 0.0494)	(0.0197, 0.0294, 0.0444)	(0.0165, 0.0247, 0.0411)
(0.0084, 0.0097, 0.0111)	(0.0084, 0.0092, 0.0104)	(0.0010, 0.0013, 0.0022)	(0.0104, 0.0129, 0.0174)	(0.0039, 0.0083, 0.0167)
(0.0371, 0.0618, 0.0866)	(0.0289, 0.0536, 0.0783)	(0.0783, 0.1031, 0.1196)	(0.0124, 0.0371, 0.0618)	(0.0701, 0.0948, 0.1154)
(0.0585, 0.0819, 0.1054)	(0.0429, 0.0663, 0.0897)	(0.0117, 0.0351, 0.0585)	(0.0585, 0.0819, 0.1054)	(0.0507, 0.0741, 0.0975)
(0.0285, 0.0374, 0.0434)	(0.0285, 0.0374, 0.0434)	(0.0075, 0.0165, 0.0255)	(0.0285, 0.0374, 0.0434)	(0.0285, 0.0374, 0.0434)
(0.2111, 0.2777, 0.3222)	(0.2111, 0.2777, 0.3222)	(0.0555, 0.1222, 0.1889)	(0.2111, 0.2777, 0.3222)	(0.2111, 0.2777, 0.3222)
(0.0249, 0.0462, 0.0675)	(0.0391, 0.0604, 0.0817)	(0.0391, 0.0604, 0.0817)	(0.0249, 0.0462, 0.0675)	(0.0533, 0.0746, 0.0959)
(0.0075, 0.0140, 0.0205)	(0.0118, 0.0183, 0.0248)	(0.0118, 0.0183, 0.0248)	(0.0075, 0.0140, 0.0205)	(0.0162, 0.0226, 0.0291)
(0.0097 0.0292 0.0486)	(0.0227, 0.0421, 0.0616)	(0.0421, 0.0616, 0.0810)	(0.0097, 0.0292, 0.0486)	(0.0356, 0.0551, 0.0745)

4) Determine the fuzzy positive-ideal solution (FPIS) S^+ and fuzzy negative-ideal solution (FNIS) S^-.

S^+ = (0.2632,0.2632,0.2632), (0.1407,0.1407,0.1407), (0.0315,0.0315,0.0315), (0.1089,0.1089,0.1089), (0.0735,0.0735,0.0735), (0.0074,0.0074,0.0074), (0.0226,0.0226,0.0226), (0.1398,0.1398,0.1398), (0.0174,0.0174,0.0174), (0.1196,0.1196,0.1196), (0.1054,0.1054,0.1054), (0.0434,0.0434,0.0434), (0.3222,0.3222,0.3222), (0.0959,0.0959,0.0959), (0.0291,0.0291,0.0291), (0.0810,0.0810,0.0810)

S^- = (0.0439,0.0439,0.0439), (0.0243,0.0243,0.0243), (0.0052,0.0052,0.0052), (0.0327,0.0327,0.0327), (0.0220,0.0220,0.0220), (0.0028,0.0028,0.0028), (0.0055,0.0055,0.0055), (0.0165,0.0165,0.0165), (0.0010,0.0010,0.001), (0.0124,0.0124,0.0124), (0.0117,0.0117,0.0117), (0.0075,0.0075,0.0075), (0.0555,0.0555,0.0555), (0.0249,0.0249,0.0249), (0.0075,0.0075,0.0075), (0.0097,0.0097,0.0097)

5) Calculate the distance of each alternative from FPIS (d^+) and FNIS (d^-) by using equation (4.16). The results of the distance both FPIS and FNIS are summarized in table 6.27.

Table 6.27. FPIS and FNIS

	d^+				
	A_1	A_2	A_3	A_4	A_5
c_1	0.1722	0.1219	0.0258	0.1219	0.1057
c_2	0.0377	0.0377	0.0905	0.0302	0.0377
c_3	0.0206	0.0206	0.0044	0.0146	0.0073
c_4	0.0254	0.0254	0.0573	0.0113	0.0504
c_5	0.0134	0.0211	0.0295	0.0140	0.0387
c_6	0.0010	0.0022	0.0029	0.0036	0.0037
c_7	0.0049	0.0131	0.0131	0.0131	0.0131
c_8	0.0777	0.0898	0.1050	0.1091	0.1129
c_9	0.0078	0.0081	0.0159	0.0048	0.0094
c_{10}	0.0612	0.0690	0.0256	0.0849	0.0320
c_{11}	0.0302	0.0434	0.0728	0.0302	0.0366
c_{12}	0.0093	0.0093	0.0279	0.0093	0.0093
c_{13}	0.0691	0.0691	0.2072	0.0691	0.0691

c_{14}	0.0527	0.0395	0.0395	0.0527	0.0275
c_{15}	0.0160	0.0120	0.0120	0.0160	0.0083
c_{16}	0.0542	0.0420	0.0251	0.0542	0.0304
$\sum$	**0.6532**	**0.6242**	**0.7546**	**0.6389**	**0.5921**

	d^-				
	A_1	A_2	A_3	A_4	A_5
c_1	0.0680	0.1137	0.2027	0.1137	0.1301
c_2	0.0885	0.0885	0.0376	0.0959	0.0885
c_3	0.0081	0.0081	0.0233	0.0136	0.0207
c_4	0.0576	0.0576	0.0281	0.0681	0.0340
c_5	0.0426	0.0352	0.0273	0.0408	0.0190
c_6	0.0039	0.0029	0.0027	0.0014	0.0010
c_7	0.0139	0.0060	0.0060	0.0060	0.0060
c_8	0.0737	0.0731	0.0221	0.0179	0.0150
c_9	0.0088	0.0084	0.0007	0.0129	0.0101
c_{10}	0.0534	0.0459	0.0896	0.0319	0.0832
c_{11}	0.0728	0.0579	0.0302	0.0728	0.0653
c_{12}	0.0296	0.0296	0.0116	0.0296	0.0296
c_{13}	0.2196	0.2196	0.0861	0.2196	0.2196
c_{14}	0.0275	0.0395	0.0395	0.0275	0.0527
c_{15}	0.0083	0.0120	0.0120	0.0083	0.0160
c_{16}	0.0251	0.0361	0.0542	0.0251	0.0481
$\sum$	**0.8014**	**0.8342**	**0.6738**	**0.7853**	**0.8389**

6) Calculate the closeness coefficient (CC_i)

$$CC_1 = \frac{0.8014}{0.6532+0.8014} = 0.55095 \qquad CC_4 = \frac{0.7853}{0.7546+0.7853} = 0.55139$$

$$CC_2 = \frac{0.8342}{0.6242+0.8342} = 0.57199 \qquad CC_5 = \frac{0.8389}{0.5921+0.8389} = 0.58623$$

$$CC_3 = \frac{0.6738}{0.6532+0.6738} = 0.47171$$

Second Stage. We would like to incorporate both qualitative and quantitative criteria into alternative selection through optimization. Besides finding the best alternative, determining the optimal number of MHE is also encompassed. Data required to construct the model are summarized in table 6.28.

Table 6.28. Data warehouse and alternatives

	A_1 Class VI	A_2 Class I	A_3 Class III	A_4 Class III	A_5 Class III
Cost:					
a) MC_i					
Lift truck ($)	235/month	235/month	180/month	200/month	200/month
Battery/Fuel ($)	183/month	300/month	30/month	35/month	35/month
TOTAL ($)	418/month 19/day	535/month 24.32/day	210/month 9.55/day	235/month 10.68/day	235/month 10.68/day
b) OC_i					
Labor cost ($)	65/month	350/month	250/month	265/month	265/month
Battery/fuel ($)	200/month	42/month	30/month	35/month	35/month
TOTAL ($)	265/month 0.025/min	392/month 0.037/min	280/month 0.027/min	300/month 0.028/min	300/month 0.028/min
c) P_i ($)	15000	20000	8200	10000	18000
d) S_i ($)	8500	10000	3800	4800	6700
F_i	6 years 1584days	6 years 1584days	6 years 1584days	6 years 1584days	6 years 1584days
Time:					
$LULT_{store,i}$ (minute)	1.7	1.7	1.8	1.8	2.4
$T_{store,i}$ (minute)	14.3	15	15.8	21.4	25
t_{store} (minute)	14.3	15	15.8	21.4	25
$LULT_{ship,i}$ (minute)	1.7	1.7	1.8	1.8	2.4
$T_{ship,i}$ (minute)	11.4	12	12.6	17.1	20
t_{ship} (minute)	11.4	12	12.6	17.1	20
E_i	1500 kg 6 pallets	1000 kg 4 pallets	2000 kg 8 pallets	1400 kg 5 pallets	1000 kg 4 pallets
CC_i	0.55095	0.57199	0.47171	0.55139	0.58623
h_i (m)	3.035	3.310	0.235	4.400	4.760

H_i (m)	2.035	2.055	0.880	2.057	2.65
b_i (m)	1.14	1.14	1.14	1.14	1.14
$H_{storage}$ (m)				2.9	
L (m)				2.8	
TH				8 hours ≈ 480 minutes	
Utility				0.85	
Demand:					
D_{store}				42 pallets/day	
D_{ship}				58 pallets/day	

Note: Company applies 1 work shift per day involving 8 hours available work and 5 work days in a week. It is assumed that there are approximately 22 work days in a month.

Stacking aisle required for each alternative can be calculated according to the formula bellow:

- $A_{st,1} = W_a + \sqrt{(l_6 + x)^2 + \left(\frac{b_{12}}{2} - b_{13}\right)^2} + a$

$= 1.72 + \sqrt{(1.07 + 0.4)^2 + \left(\frac{1.14}{2} - 0.472\right)^2} + 0.2 = 1.72+1.47+0.2 = 3.39$ m

- $A_{st,2} = W_a + \sqrt{(l_6 + x)^2 + \left(\frac{b_{12}}{2}\right)^2} + a$

$= 1.23 + \sqrt{(0.8 + 0.33)^2 + \left(\frac{1.14}{2}\right)^2} + 0.2 = 1.23 + 1.27 + 0.2 = 2.7$ m

$A_{st,3} = W_a - x + l_6 + a$

$= 1.855 - 0.958 + 1.15 + 0.2 = 2.247$ m

- $A_{st,4} = W_a + \sqrt{(l_6 - x)^2 + \left(\frac{b_{12}}{2}\right)^2} + a$

$= 1.649 + \sqrt{(1.15 - 0.418)^2 + \left(\frac{1.14}{2}\right)^2} + 0.2 = 1.649 + 0.93 + 0.3 = 2.779$ m

- $A_{st,5} = W_a + \sqrt{(l_6 + x)^2 + \left(\frac{b_{12}}{2}\right)^2} + a$

$= 1.66 + \sqrt{(0.9 + 0.225)^2 + \left(\frac{1.14}{2}\right)^2} + 0.2 = 1.66 + 1.26 + 0.2 = 3.12$ m

According to the developing model of MHE selection in session 5.2, finally the MHE selection problem is constructed as follows:

Objective functions

1) Minimize disadvantages of use Z_1 (X,Y)

Min (1-0.55095).2.$X_1.Y_1$ + (1-0.57199).2.$X_2.Y_2$ + (1-0.47171).2.$X_3.Y_3$ + (1-0.55139).2. $X_4.Y_4$ + (1-0.58623).2. $X_5.Y_5$

2) Minimize total cost of material handling Z_2 (X,Y)

$$\text{Min } X_1.Y_1(\left(\frac{15000-8500}{1584}\right)+19)+\left(\frac{42x30{,}3+58x24{,}5}{X_1 2}\right)12{,}5.Y_1+ X_2.Y_2(\left(\frac{20000-10000}{1584}\right)+24{,}32)+\left(\frac{42x31{,}7+58x25{,}7}{X_2 2}\right)17{,}82.Y_2+X_3.Y_3\left(\left(\frac{8200-3800}{1584}\right)+9.55\right)+\left(\frac{42x33{,}4+58x27}{X_3 2}\right)13{,}64.Y_3+X_4.Y_4(\left(\frac{10000-4800}{1584}\right)+10{,}68)+\left(\frac{42x44{,}6+58x36}{X_4 2}\right)13{,}64.Y_4+X_5.Y_5(\left(\frac{18000-6700}{1584}\right)+10.68)+\left(\frac{42x52{,}4+58x42{,}4}{X_5 2}\right)13{,}64.Y_5$$

s.t

$Y_1 + Y_2 + Y_3 + Y_4 + Y_5 = 1$

$$0{,}85.480 \le Y_1\left(\frac{42x30{,}3+58x24{,}5}{X_1.2}\right)+Y_2\left(\frac{42x31{,}7+58x25{,}7}{X_2.2}\right)+Y_3\left(\frac{42x33{,}4+58x27}{X_3.2}\right)+Y_4\left(\frac{42x44{,}6+58x36}{X_4.2}\right)+Y_5\left(\frac{42x52{,}4+58x42{,}4}{X_5.2}\right) \le 480$$

$Y_1 .3{,}035 + Y_2 .3{,}310 + Y_3 .0{,}235 + Y_4 .4{,}4 + Y_5 .4{,}76 \ge 2.9$

$Y_1 .1{,}14 + Y_2 .1{,}14 + Y_3 .1{,}14 + Y_4 .1{,}14 + Y_5 .1{,}14 \ge 2.8$

$Y_1 .6 + Y_2 .4 + Y_3 .8 + Y_4 .5 + Y_5 .4 \ge 2$

$Y_1 .3{,}39 + Y_2 .2{,}7 + Y_3 .2.247 + Y_4 .2.779 + Y_5 .3.12 \ge 2.8$

$X_1, X_2, X_3, X_4, X_5 \ge 0$ and Integer

$Y_1, Y_2, Y_3, Y_4, Y_5 = 0$ or 1

To solve MOMILP model above, augmented e-constraint (AUGMECON) procedure is used. First, payoff table will be constructed by using lexicographic method with the prioritized objective function is addressed to disadvantage of use minimization or Z1 (see table 6.29).

Table 6.29. payoff table of objective function Z1 & Z2

	Z1	Z2
Min Z1	2.568060	103.65849
Min Z2	2.568080	103.6577
r_2		0.00079

Then, MOMILP model Z1 (e_1) is transformed becomes:

Min (f_1(x) + eps (s_{p2}/ r_2))

st

f_2(x) + s_{p2} = e_2

Min (1-0.55095).2.Y_1 + (1-0.57199).2.Y_2 + (1-0.47171).2.Y_3 +(1-0.55139).2.Y_4 +(1-0.58623).2.Y_5 + 10^{-4} ($\frac{s_{p2}}{0.00079}$)

st

$X_1.Y_1(\left(\frac{15000-8500}{1584}\right) + 19) + \left(\frac{42x30,3+58x24,5}{X_1.2}\right)0,025.Y_1 + \quad X_2.Y_2(\left(\frac{20000-10000}{1584}\right) + 24,32) + \left(\frac{42x31,7+58x25,7}{X_2.2}\right)0,037.Y_2 + X_3.Y_3\left(\left(\frac{8200-3800}{1584}\right) + 9.55\right) + \left(\frac{42x33,4+58x27}{X_3.2}\right)0,027.Y_3 \ + X_4.Y_4(\left(\frac{10000-4800}{1584}\right) + 10,68) + \left(\frac{42x44,6+58x36}{X_4.2}\right)0,028.Y_4 + X_5.Y_5(\left(\frac{18000-6700}{1584}\right) + 10.68) + \left(\frac{42x52,4+58x42,4}{X_5.2}\right)0,028.Y_5 + s_{p2} = 103.6577$

Solution is obtained by using LINGO software. The result shows that the best MHE for warehouse operation in the company particularly as transport, picking, and loading unloading material equipment is electronic counterbalanced truck (A2). Based on the LINGO software output, objective value achievement for objective function 1 (Z1) and 2 (Z2) are respectively 2.568060 and $103.6577 per day. The number of MHE required (X_2) is 3 units.

CHAPTER 7
CONCLUSIONS

In this thesis MHE selection problem is defined as MCDM under fuzzy environment and multi objective problem. To deal with alternatives selection, MHE is evaluated under 4 criteria and 16 sub-criteria by using hierarchical fuzzy TOPSIS. Fuzzy set theory is applied to TOPSIS and AHP because the evaluation parameters cannot be measured and predicted precisely such assessing alternative according to its safety, user friendliness and flexibility which contain intangible information will lead DMs to the subjectivity and imprecise judgment. In order to enhance the DMs' opinion, fuzzy set was applied. The extension of fuzzy TOPSIS in determining criteria weight by using fuzzy AHP is thoroughly remarkable. It is really useful to buttress the arbitrary DM's opinion in assessing the evaluation criteria. Moreover, entropy method is adopted to obtain objective weight of evaluation criteria and integrate it with subjective weight derived from fuzzy AHP. Entropy method is meaningful since quantitative data is available. In this study, information regarding alternative specifications particularly such as speed (km/h), load capacity (kg), and lift height (m) are factually provided. To tackle the objective criteria according to the behavior of real data, entropy method is able to measure which information is more useful. The more useful information should be set high correspondingly among other. According to the entropy method, load capacity contains the largest amount of information and difference of evaluation index. The rank order of criteria has changed after applying integration of subjective and objective weight (see table 7.1). The difference can be seen explicitly at the rank order of load capacity is upgraded on the fourth order where previously it was on the tenth order among other criteria obtained from fuzzy AHP. It was evident that measuring weight just by looking at subjective weight and neglecting the objective weight doesn't reflect the essence of information.

The results show that among four criteria (operational capability, technical parameters, compatibility, and maintainability), compatibility is the most critical criterion to be taken for granted. While among sixteen sub criteria, storage system, safety and user friendliness are critical consideration for selecting MHE in warehouse.

Table 7.1. Subjective & integrated weight of sub-criteria

Sub-criteria	Subjective weight		Integrated weigt	
	weight (W)	Priority	weight (W)	Priority
Safety (c_1)	0.263	2	0.263	2
User friendliness (c_2)	0.141	3	0.141	3
Operator skill requirement (c_3)	0.031	13	0.031	12
Task Application (c_4)	0.109	5	0.109	6
Flexibility (c_5)	0.073	11	0.073	10
Speed (c_6)	0.010	16	0.007	16*
Power Requirement (c_7)	0.023	15	0.023	14
Load Capacity (c_8)	0.058	10	0.140	4*
Lift Height (c_9)	0.074	9	0.017	15*
Aisle width (c_{10})	0.120	4	0.120	5
Rack Height (c_{11})	0.105	6	0.105	7
Door way height (c_{12})	0.043	12	0.043	11
Storage system (c_{13})	0.322	1	0.322	1
Spare part Acquirement (c_{14})	0.096	7	0.096	8
On-site technical assistance (c_{15})	0.029	14	0.029	13
Maintenance training (c_{16})	0.081	8	0.081	9

*) indicates integrated weight

Here we have 5 alternatives namely IC counterbalanced truck (A1), E-counterbalanced truck (A2), Pallet truck (A3), Reach truck (A4), and Order picker (A5). By using same procedure of hierarchical fuzzy TOPSIS, for instant, the result of alternatives rating and ranking corresponding under subjective weight and integrated weight are compared in table 8.2. In this context, looking at the different considerations on weight of evaluation criteria determination such in table above literally brings different result regarding the rank order of alternatives. The alternative selection obtained from hierarchical fuzzy TOPSIS suggested that the most suitable MHE for warehouse operations is order picker (A5).

The decision would be more distracting if the problem is a multi-alternative selection which means there are more than one alternative to be chosen. In this context, looking at the different considerations of weight of evaluation criteria determination such in table 7.2 literally brings different rank order of alternative. In the case of applying subjective weight of criteria, alternative 5 & 2 can be taken for granted whereas alternative 5 & 4 are eligible for the selection in accordance with integrated weight.

Table 7.2. Comparison of Alternatives rank using initial weight and integrated weigh of evaluation criteria (sub-criteria)

Alternatives	Subjective weight		Integrated weight	
	Rating	Rank	Rating	Rank
A1	0.55095	4	0.55451	4
A2	0.57199	2	0.57783	3
A3	0.47171	5	0.47101	5
A4	0.55139	3	0.57979	2
A5	0.58623	1	0.60742	1

In view of comprehensive decision making, selection process is conducted by considering holistic parameters. At this view point, alternative selection is expected to be able to contribute the continuity of warehouse operations as well as handling material and the expense for the alternative should be worth for the value given to material, operator and operations itself. In other words, alternative should meet both goals that are minimization of disadvantages of use and total cost of material handling. To achieve those goals, MHE selection problem is translated into MOMILP. MOMILP was developed for suited based practice of MHE selection problem. The developed model aims to seek the best alternative satisfying both objective function and determine the required number of alternative. MOMILP model is solved through AUGMECON method so that the superior goal that is minimization of disadvantage of use (goal 1) can be achieved first and minimization of material handling cost (goal 2) can be subsequently satisfied. We will delve into final solution by using MOMILP and apply rating of alternative derived from subjective and integrated weight into model (5) partially. By using LINGO software, solution for both scenarios suggest same alternative to be selected (see Appendix B.1 & B.2). Finally, the solution brings MHE selection problem a comprehensive and holistic selection process by offering the best one. The final result of alternative selection through AUGMECON shows that the most suitable MHE for warehouse operations is E-counterbalanced truck (A2). The required number of E-counterbalanced truck is 3 units. The optimal number of MHE is calculated to fulfill the warehouse operation in terms of handling product received and shipped within 8 hours working. The achievement value for goal 1 and goal 2 respectively is 2.568060 and $103.6577 per day.

If we look at the first stage of alternative selection conducted by using hierarchical fuzzy TOPSIS, there is a contrast difference result. It is admitted that A5 is the suitable alternative. But it is no longer visible since the minimum total cost of material handling couldn't be addressed to A5. For complex decision making, alternative selection cannot be established only by using a stand-alone MCDM method because most of MCDM method just encounter evaluation trough subjectivity of human's judgment instead of exact quantified algorithm.

In addition, as further discussion, the complexity of decision making will increase for multi-alternative selection. Applying different weight of evaluation criteria will result different rank order of alternative. Two scenarios were made by applying different weight to enlighten the superiority of proposed hybrid method in finding the most suitable alternative. The visible solution was derived from extended approach according to optimization by using AUGMECON. The result showed the same solution for both scenarios. It indicates that using extended approach for MCDM as well as optimization can shrink the dilemmatic selection of alternative which may lead to improper decision making and offer more accurate solution.

To conclude this work, it is worth to highlight the advantages of the proposed method. The hybrid method of entropy based hierarchical fuzzy TOPSIS and MOMILP brings some enormous advantages for MHE selection:

1) The proposed hybrid method can represent the actual provided data into criteria evaluation and more measured weight of criteria.

2) MCDM method cannot provide better result for complex MHE selection problem if it stands alone. Hence, Integration of entropy based hierarchical fuzzy TOPSIS and MOMILP can provide more accurate result.

3) The proposed hybrid method is capable to fulfill the performance measure of the most suitable MHE in terms of operational capability, technical parameters, compatibility, maintainability and cost as well.

4) The hybrid method doesn't attempt for only finding the most suitable MHE (Braglia, et al. 2001; Chan et al., 2001) but also determining the optimum number of MHE.

The future work is expected for improvement of current study. Current study just develop model for MHE selection problem in warehouse for single product. The hybrid model may be improved for MHE selection for warehouse of heterogeneous or multi-product. However, there are several methods of MCDM such PROMETHER, ELECTRE, ANP and many more which may be able to be combined with optimization method.

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APPENDICES

APPENDIX A.1. Pair wise comparison matrices

DM1	Safety	User friendliness	Operator skill requirement	Task Application	Flexibility
Safety	1	3	5	2	4
User friendliness	1/3	1	5	1/2	2
Operator skill requirement	1/5	1/5	1	1/5	1/2
Task Application	1/2	2	5	1	3
Flexibility	1/4	1/2	2	1/3	1
DM2	Safety	User friendliness	Operator skill requirement	Task Application	Flexibility
Safety	1	2	7	5	3
User friendliness	1/2	1	5	3	2
Operator skill requirement	1/7	1/5	1	1/2	1/5
Task Application	1/5	1/3	2	1	1/3
Flexibility	1/3	1/2	5	3	1
DM3	Safety	User friendliness	Operator skill requirement	Task Application	Flexibility
Safety	1	3	7	3	5
User friendliness	1/3	1	6	1	4
Operator skill requirement	1/7	1/6	1	1/5	1/2
Task Application	1/3	1	5	1	3
Flexibility	1/5	1/4	2	1/3	1

DM1	Speed	Power Requirement	Load Capacity	Lift Height
Speed	1	1/3	1/7	1/6
Power Requirement	3	1	1/5	1/3
Load Capacity	7	5	1	2
Lift Height	6	3	1/2	1
DM2	Speed	Power Requirement	Load Capacity	Lift Height
Speed	1	1/3	1/5	1/7
Power Requirement	3	1	1/3	1/5
Load Capacity	5	3	1	1/3
Lift Height	7	5	3	1
DM3	Speed	Power Requirement	Load Capacity	Lift Height
Speed	1	1/2	1/6	1/9
Power Requirement	2	1	1/3	1/6
Load Capacity	6	3	1	1/2
Lift Height	9	6	2	1

DM1	Aisle width	Rack Height	Height of door way	Storage system
Aisle width	1	3	5	1/3
Rack Height	1/3	1	3	1/5
Height of door way	1/5	1/3	1	1/8
Storage system	3	5	8	1
DM2	Aisle width	Rack Height	Height of door way	Storage system
Aisle width	1	1/4	3	1/6
Rack Height	4	1	5	1/2
Height of door way	1/3	1/5	1	1/7
Storage system	6	2	7	1
DM3	Aisle width	Rack Height	Height of door way	Storage system
Aisle width	1	2	4	1/3
Rack Height	1/2	1	2	1/5
Height of door way	1/4	1/2	1	1/7
Storage system	3	5	7	1

DM1	Spare part Acquirement	On-site technical assistance	Maintenance training
Spare part Acquirement	1	3	2
On-site technical assistance	1/3	1	1/3
Maintenance training	1/2	3	1
DM2	Spare part Acquirement	On-site technical assistance	Maintenance training
Spare part Acquirement	1	3	1/2
On-site technical assistance	1/3	1	1/7
Maintenance training	2	7	1
DM3	Spare part Acquirement	On-site technical assistance	Maintenance training
Spare part Acquirement	1	5	2
On-site technical assistance	1/5	1	1/3
Maintenance training	1/2	3	1

APPENDIX A.2. Consistency Test

DM1	C1	C2	C3	C4	W	V	λ	λ_{max}	CI	CR
Operational Capability	0.394	0.384	0.387	0.409	0.393	1.612	4.092	4.067	0.022	0.0249
Technical Parameters	0.078	0.076	0.096	0.045	0.074	0.299	4.015	CR≤0.1 RI = 0.9		
Compatibility	0.394	0.307	0.387	0.409	0.374	1.537	4.103			
Maintainability	0.131	0.230	0.129	0.136	0.156	0.636	4.057			
DM2	C1	C2	C3	C4	W	V	λ	λ_{max}	CI	CR
Operational Capability	0.492	0.455	0.522	0.462	0.482	1.940	4.021	4.014	0.004	0.0054
Technical Parameters	0.098	0.091	0.087	0.077	0.088	0.354	4.011	CR≤0.1 RI = 0.9		
Compatibility	0.246	0.273	0.261	0.308	0.272	1.093	4.021			
Maintainability	0.164	0.182	0.130	0.154	0.158	0.631	4.005			
DM3	C1	C2	C3	C4	W	V	λ	λ_{max}	CI	CR
Operational Capability	0.218	0.321	0.199	0.267	0.251	1.056	4.201	4.121	0.040	0.0447
Technical Parameters	0.073	0.107	0.119	0.200	0.125	0.503	4.029	CR≤0.1 RI = 0.9		
Compatibility	0.655	0.536	0.597	0.467	0.563	2.365	4.198			
Maintainability	0.055	0.036	0.085	0.067	0.061	0.245	4.054			

DM1	c_{11}	c_{21}	c_{31}	c_{41}	c_{51}	W	V	λ	λ_{max}	CI	CR
Safety	0.438	0.448	0.278	0.496	0.381	0.408	2.121	5.197	5.122	0.03	0.0272
User friendliness	0.146	0.149	0.278	0.124	0.190	0.177	0.906	5.104	CR≤0.1 RI = 1.12		
Operator skill requirement	0.088	0.030	0.056	0.050	0.048	0.054	0.272	5.026			
Task Application	0.219	0.299	0.278	0.248	0.286	0.266	1.379	5.188			
Flexibility	0.109	0.075	0.111	0.083	0.095	0.095	0.482	5.095			

DM2	c_{11}	c_{21}	c_{31}	c_{41}	c_{51}	W	V	λ	$λ_{max}$	CI	CR
Safety	0.460	0.496	0.350	0.400	0.459	0.433	2.230	5.152	5.094	0.024	0.0211
User friendliness	0.230	0.248	0.250	0.240	0.306	0.255	1.318	5.175	CR≤0.1 RI = 1.12		
Operator skill requirement	0.066	0.050	0.050	0.040	0.031	0.047	0.237	5.032			
Task Application	0.092	0.083	0.100	0.080	0.051	0.081	0.408	5.034			
Flexibility	0.153	0.124	0.250	0.240	0.153	0.184	0.935	5.080			
DM3	c_{11}	c_{21}	c_{31}	c_{41}	c_{51}	W	V	λ	$λ_{max}$	CI	CR
Safety	0.498	0.554	0.333	0.542	0.370	0.459	2.409	5.244	5.120	0.030	0.0267
User friendliness	0.166	0.185	0.286	0.181	0.296	0.223	1.141	5.127	CR≤0.1 RI = 1.12		
Operator skill requirement	0.071	0.031	0.048	0.036	0.037	0.045	0.224	5.040			
Task Application	0.166	0.185	0.238	0.181	0.222	0.198	1.022	5.153			
Flexibility	0.100	0.046	0.095	0.060	0.074	0.075	0.378	5.034			

DM1	c_{12}	c_{22}	c_{32}	c_{42}	W	V	λ	$λ_{max}$	CI	CR
Speed	0.059	0.036	0.078	0.048	0.055	0.220	4.014	4.068	0.023	0.0252
Power Requirement	0.176	0.107	0.109	0.095	0.122	0.492	4.040	CR≤0.1 RI = 0.90		
Load Capacity	0.412	0.536	0.543	0.571	0.515	2.125	4.123			
Lift Height	0.353	0.321	0.271	0.286	0.308	1.261	4.095			
DM2	c_{12}	c_{22}	c_{32}	c_{42}	W	V	λ	$λ_{max}$	CI	CR
Speed	0.063	0.036	0.044	0.085	0.057	0.230	4.041	4.118	0.039	0.0439
Power Requirement	0.188	0.107	0.074	0.119	0.122	0.492	4.036	CR≤0.1 RI = 0.90		
Load Capacity	0.313	0.321	0.221	0.199	0.263	1.099	4.175			
Lift Height	0.438	0.536	0.662	0.597	0.558	2.356	4.222			

DM3	c_{12}	c_{22}	c_{32}	c_{42}	W	V	λ	λ_{max}	CI	CR
Speed	0.056	0.048	0.048	0.063	0.053	0.213	4.002	4.010	0.003	0.0038
Power Requirement	0.111	0.095	0.095	0.094	0.099	0.396	4.009	CR≤0.1 RI = 0.90		
Load Capacity	0.333	0.286	0.286	0.281	0.297	1.189	4.009			
Lift Height	0.500	0.571	0.571	0.563	0.551	2.217	4.022			

DM1	c_{13}	c_{23}	c_{33}	c_{43}	W	V	λ	λ_{max}	CI	CR
Aisle width	0.221	0.321	0.294	0.201	0.259	1.074	4.144	4.094	0.031	0.0349
Rack Height	0.074	0.107	0.176	0.121	0.119	0.480	4.018	CR≤0.1 RI = 0.90		
Height of door way	0.044	0.036	0.059	0.075	0.054	0.216	4.040			
Storage system	0.662	0.536	0.471	0.603	0.568	2.371	4.176			
DM2	c_{13}	c_{23}	c_{33}	c_{43}	W	V	λ	λ_{max}	CI	CR
Aisle width	0.088	0.072	0.188	0.092	0.110	0.446	4.053	4.122	0.041	0.0451
Rack Height	0.353	0.290	0.313	0.276	0.308	1.297	4.211	CR≤0.1 RI = 0.90		
Height of door way	0.029	0.058	0.063	0.079	0.057	0.230	4.028			
Storage system	0.529	0.580	0.438	0.553	0.525	2.202	4.195			
DM3	c_{13}	c_{23}	c_{33}	c_{43}	W	V	λ	λ_{max}	CI	CR
Aisle width	0.211	0.235	0.286	0.199	0.233	0.936	4.025	4.028	0.009	0.0105
Rack Height	0.105	0.118	0.143	0.119	0.121	0.487	4.019	CR≤0.1 RI = 0.90		
Height of door way	0.053	0.059	0.071	0.085	0.067	0.269	4.006			
Storage system	0.632	0.588	0.500	0.597	0.579	2.352	4.062			

DM1	c_{14}	c_{24}	c_{34}	W	V	λ	λ_{max}	CI	CR
Spare part Acquirement	0.545	0.429	0.600	0.525	1.617	3.082	3.054	0.027	0.0464
On-site technical assistance	0.182	0.143	0.100	0.142	0.428	3.021	CR≤0.1 RI = 0.58		
Maintenance training	0.273	0.429	0.300	0.334	1.021	3.058			
DM2	c_{14}	c_{24}	c_{34}	W	V	λ	λ_{max}	CI	CR
Spare part Acquirement	0.300	0.273	0.304	0.292	0.878	3.002	3.003	0.001	0.0023
On-site technical assistance	0.100	0.091	0.087	0.093	0.278	3.001	CR≤0.1 RI = 0.58		
Maintenance training	0.600	0.636	0.609	0.615	1.848	3.005			

DM3	c_{14}	c_{24}	c_{34}	W	V	λ	λ_{max}	CI	CR
Spare part Acquirement	0.588	0.556	0.600	0.581	1.747	3.006	3.004	0.002	0.0032
On-site technical assistance	0.118	0.111	0.100	0.110	0.329	3.001	CR≤0.1 RI = 0.58		
Maintenance training	0.294	0.333	0.300	0.309	0.929	3.004			

APPENDIX A.3. Fuzzy Pair wise comparison matrices

DM1	Safety	User friendlines	Operator skill requirement	Task Apllication	Flexiblelity
Safety	(1,1,1)	(1,3,5)	(3,5,7)	(1,2,3)	(2,4,6)
User friendlines	(1/5,1/3,1)	(1,1,1)	(3,5,7)	(1/3,1/2,1)	(1,2,3)
Operator skill requirement	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1,1,1)	(1/7,1/5,1/3)	(1/3,1/2,1)
Task Apllication	(1/3,1/2,1)	(1,2,3)	(3,5,7)	(1,1,1)	(1,3,5)
Flexiblelity	(1/6,1/4,1/2)	(1/3,1/2,1)	(1,2,3)	(1/5,1/3,1)	(1,1,1)
DM2	Safety	User friendlines	Operator skill requirement	Task Apllication	Flexiblelity
Safety	(1,1,1)	(1,2,3)	(5,7,9)	(3,5,7)	(1,3,5)
User friendlines	(1/3,1/2,1)	(1,1,1)	(3,5,7)	(1,3,5)	(1,2,3)
Operator skill requirement	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1,1,1)	(1/3,1/2,1)	(1/7,1/5,1/3)
Task Apllication	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,2,3)	(1,1,1)	(1/5,1/3,1)
Flexiblelity	(1/5,1/3,1)	(1/3,1/2,1)	(3,5,7)	(1,3,5)	(1,1,1)
DM3	Safety	User friendlines	Operator skill requirement	Task Apllication	Flexiblelity
Safety	(1,1,1)	(1,3,5)	(5,7,9)	(1,3,5)	(3,5,7)
User friendlines	(1/5,1/3,1)	(1,1,1)	(4,6,8)	(1,1,1)	(2,4,6)
Operator skill requirement	(1/9,1/7,1/5)	(1/8,1/6,1/4)	(1,1,1)	(1/7,1/5,1/3)	(1/3,1/2,1)
Task Apllication	(1/5,1/3,1)	(1,1,1)	(3,5,7)	(1,1,1)	(1,3,5)
Flexiblelity	(1/7,1/5,1/3)	(1/6,1/4,1/2)	(1,2,3)	(1/5,1/3,1)	(1,1,1)

DM1	Speed	Power Requirement	Load Capacity	Lift Height
Speed	(1,1,1)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/8,1/6,1/4)
Power Requirement	(1,3,5)	(1,1,1)	(1/7,1/5,1/3)	(1/5,1/3,1)
Load Capacity	(5,7,9)	(3,5,7)	(1,1,1)	(1,2,3)
Lift Height	(4,6,8)	(1,3,5)	(1/7,1/5,1/3)	(1,1,1)
DM2	Speed	Power Requirement	Load Capacity	Lift Height
Speed	(1,1,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/9,1/7,1/5)
Power Requirement	(1,3,5)	(1,1,1)	(1/5,1/3,1)	(1/7,1/5,1/3)
Load Capacity	(3,5,7)	(1,3,5)	(1,1,1)	(1/5,1/3,1)
Lift Height	(5,7,9)	(3,5,7)	(1,3,5)	(1,1,1)
DM3	Speed	Power Requirement	Load Capacity	Lift Height
Speed	(1,1,1)	(1/7,1/5,1/3)	(1/8,1/6,1/4)	(1/9,1/9,1/7)
Power Requirement	(1,2,3)	(1,1,1)	(1/5,1/3,1)	(1/8,1/6,1/4)
Load Capacity	(4,6,8)	(1,3,5)	(1,1,1)	(1/7,1/5,1/3)
Lift Height	(7,9,9)	(4,6,8)	(1,2,3)	(1,1,1)

DM1	Aisle width	Rack Height	Height of door way	Storage system
Aisle width	(1,1,1)	(1,3,5)	(3,5,7)	(1/5,1/3,1)
Rack Height	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1/7,1/5,1/3)
Height of door way	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,1,1)	(1/9, 1/8, 1/6)
Storage system	(1,3,5)	(3,5,7)	(6,8,9)	(1,1,1)
DM2	Aisle width	Rack Height	Height of door way	Storage system
Aisle width	(1,1,1)	(1/6,1/4,1/2)	(1,3,5)	(1/8,1/6,1/4)
Rack Height	(2,4,6)	(1,1,1)	(3,5,7)	(1/3,1/2,1)
Height of door way	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,1,1)	(1/9,1/7,1/5)
Storage system	(4,6,8)	(1,2,3)	(5,7,9)	(1,1,1)
DM3	Aisle width	Rack Height	Height of door way	Storage system
Aisle width	(1,1,1)	(1,2,3)	(2,4,6)	(1/5,1/3,1)
Rack Height	(1/3,1/2,1)	(1,1,1)	(1,2,3)	(1/7,1/5,1/3)
Height of door way	(1/6,1/4,1/2)	(1/3,1/2,1)	(1,1,1)	(1/9,1/7,1/5)
Storage system	(1,3,5)	(3,5,7)	(5,7,9)	(1,1,1)

DM1	Spare part Acquirement	On-site technical assistance	Maintenance training
Spare part Acquirement	(1,1,1)	(1,3,5)	(1,2,3)
On-site technical assistance	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)
Maintenance training	(1/3,1/2,1)	(1,3,5)	(1,1,1)
DM2	Spare part Acquirement	On-site technical assistance	Maintenance training
Spare part Acquirement	(1,1,1)	(1,3,5)	(1/3,1/2,1)
On-site technical assistance	(1/5,1/3,1)	(1,1,1)	(1/9,1/7,1/5)
Maintenance training	(1,2,3)	(5,7,9)	(1,1,1)
DM3	Spare part Acquirement	On-site technical assistance	Maintenance training
Spare part Acquirement	(1,1,1)	(3,5,7)	(1,2,3)
On-site technical assistance	(1/7,1/5,1/3)	(1,1,1)	(1/5,1/3,1)
Maintenance training	(1/3,1/2,1)	(1,3,5)	(1,1,1)

APPENDIX A.4. Aggregated fuzzy pair-wise comparison matrices

Operational Capability	Safety	User friendliness	Operator skill requirement	Task Application	Flexibility
Safety	(1,1,1)	(1, 2.621, 4.217)	(4.217, 6.257, 8.277)	(1.442, 3.107, 4.718)	(1.817, 3.915, 5.944)
User friendliness	(0.237, 0.382, 1)	(1,1,1)	(3.302, 5.313, 7.319)	(0.693, 1.145, 1.710)	(1.260, 2.520, 3.780)
Operator skill requirement	(0.121, 0.160, 0.237)	(0.137, 0.188, 0.303)	(1,1,1)	(0.189, 0.271, 0.481)	(0.251, 0.368, 0.693)
Task Application	(0.212, 0.322, 0.630)	(0.585, 0.874, 1.442)	(2.080, 3.684, 5.278)	(1,1,1)	(0.585, 1.442, 2.924)
Flexibility	(0.005, 0.255, 0.550)	(0.265, 0.397, 0.794)	(1.442, 2.714, 3.979)	(0.342, 0.693, 1.710)	(1,1,1)

Technical Parameter	Speed	Power Requirement	Load Capacity	Lift Height
Speed	(1,1,1)	(0.179, 0.281, 0.693)	(0.126, 0.168, 0.255)	(0.116, 0.138, 0.193)
Power Requirement	(1, 2.621, 4.217)	(1,1,1)	(0.179, 0.281, 0.693)	(0.153, 0.223, 0.437)
Load Capacity	(3.915, 5.944, 7.958)	(1.442, 3.557, 5.593)	(1,1,1)	(0.306, 0.511, 1)
Lift Height	(5.192, 7.230, 8.653)	(2.289, 4.481, 6.542)	(0.523, 1.063, 1.710)	(1,1,1)

Compatibility	Aisle width	Rack Height	Height of door way	Storage system
Aisle width	(1,1,1)	(0.550, 1.145, 1.957)	(1.817, 3.915, 5.944)	(0.171, 0.265, 0.630)
Rack Height	(0.511, 0.874, 1.817)	(1,1,1)	(1.442, 3.107, 4.718)	(0.189, 0.271, 0.481)
Height of door way	(0.168, 0.255, 0.550)	(0.212, 0.322, 0.693)	(1,1,1)	(0.111, 0.137, 0.400)
Storage system	(1.587, 3.557, 5.848)	(2.080, 3.684, 5.278)	(5.313, 7.319, 9)	(1,1,1)

Maintainability	Spare part Acquirement	On-site technical assistance	Maintenance training
Spare part Acquirement	(1,1,1)	(1.442, 3.557, 5.593)	(0.693, 1.260, 2.080)
On-site technical assistance	(0.179, 0.281, 0.693)	(1,1,1)	(0.164, 0.251, 0.585)
Maintenance training	(0.481, 0.794, 1)	(1.710, 3.979, 6.082)	(1,1,1)

APPENDIX B.1. Lingo input & output for MHE selection by using AUGMECON: Integrated weight

```
SETS:
DECISION/1..5/:X;
BINARY/1..5/:Y;
DEVIATION/1/:s;
ENDSETS

DATA:
!Maintenanace cost;
MC1=19;
MC2=24.32;
MC3=9.55;
MC4=10.68;
MC5=10.68;
!Operating cost;
OC1=0.025;
OC2=0.037;
OC3=0.027;
OC4=0.028;
OC5=0.028;
!Purchase cost;
P1=15000;
P2=20000;
P3=8200;
P4=10000;
P5=18000;
!Salvage value;
S1=8500;
S2=10000;
S3=3800;
S4=4800;
S5=6700;
!Expected life;
F=1584;
!Weight;
W1=0.55095;
W2=0.57199;
W3=0.47171;
W4=0.55139;
W5=0.58623;
!Lift height;
h1=3.035;
h2=3.310;
h3=0.235;
h4=4.4;
h5=4.76;
!width of MHE;
b1=1.14;
b2=1.14;
b3=1.14;
b4=1.14;
b5=1.14;
!Load capacity;
E1=6;
E2=4;
E3=8;
E4=5;
E5=4;
```

```
!Stacking Aisle;
A1=3.39;
A2=2.7;
A3=2.247;
A4=2.779;
A5=3.12;
H=2.9;
L=2.8;
TH=480;
DST=42;
DSH=58;
Emax=2;
ENDDATA

MIN=(1-W1)*Emax*X(1)*Y(1)+(1-W2)*Emax*X(2)*Y(2)+(1-
W3)*Emax*X(3)*Y(3)+(1-W4)*Emax*X(4)*Y(4)+(1-
W5)*Emax*X(5)*Y(5)+0.00001*s(1)/0.00079;

X(1)*Y(1)*(P1-
S1)/F+X(1)*Y(1)*MC1+1346.8*OC1*Y(1)/X(1)+X(2)*Y(2)*(P2-
S2)/F+X(2)*Y(2)*MC2+1411*OC1*Y(2)/X(2)+X(3)*Y(3)*(P3-
S3)/F+X(3)*Y(3)*MC3+1484.4*OC3*Y(3)/X(3)+X(4)*Y(4)*(P4-
S4)/F+X(4)*Y(4)*MC4+1980.6*OC1*Y(4)/X(4)+X(5)*Y(5)*(P5-
S5)/F+X(5)*Y(5)*MC5+2330*OC1*Y(5)/X(5)+s(1)=103.6577;

Y(1)+Y(2)+Y(3)+Y(4)+Y(5)=1;

Y(1)*A1+Y(2)*A2+Y(3)*A3+Y(4)*A4+Y(5)*A5<=L;

Y(1)*b1+Y(2)*b2+Y(3)*b3+Y(4)*b4+Y(5)*b5<=L;

Y(1)*E1+Y(2)*E2+Y(3)*E3+Y(4)*E4+Y(5)*E5>=Emax;

h1*Y(1)+h2*Y(2)+h3*Y(3)+h4*Y(4)+h5*Y(5)>=H;

(1346.8/X(1))*Y(1)+(1411/X(2))*Y(2)+(1484.4/X(3))*Y(3)+(1980.6/X(4))
*Y(4)+(2330/X(5))*Y(5)<=480;
408<=(1346.8/X(1))*Y(1)+(1411/X(2))*Y(2)+(1484.4/X(3))*Y(3)+(1980.6/
X(4))*Y(4)+(2330/X(5))*Y(5);
@FOR(BINARY:@BIN(Y));@FOR(DECISION:@GIN(X));
END
```

Linearization components added:
Constraints: 120
Variables: 30

Objective value:	2.568060
Objective bound:	2.568060
Infeasibilities:	0.2727273E-04
Extended solver steps:	11
Total solver iterations:	821

Variable	Value
MC1	19.00000
MC2	24.32000
MC3	9.550000
MC4	10.68000
MC5	10.68000
OC1	0.2500000E-01
OC2	0.3700000E-01
OC3	0.2700000E-01
OC4	0.2800000E-01
OC5	0.2800000E-01
P1	15000.00
P2	20000.00
P3	8200.000
P4	10000.00
P5	18000.00
S1	8500.000
S2	10000.00
S3	3800.000
S4	4800.000
S5	6700.000
F	1584.000
W1	0.5509500
W2	0.5719900
W3	0.4717100
W4	0.5513900
W5	0.5862300
H1	3.035000
H2	3.310000
H3	0.2350000
H4	4.400000
H5	4.760000
B1	1.140000
B2	1.140000

B3	1.140000
B4	1.140000
B5	1.140000
E1	6.000000
E2	4.000000
E3	8.000000
E4	5.000000
E5	4.000000
A1	3.390000
A2	2.700000
A3	2.247000
A4	2.779000
A5	3.120000
H	2.900000
L	2.800000
TH	480.0000
DST	42.00000
DSH	58.00000
EMAX	2.000000
X(1)	1.000000
X(2)	3.000000
X(3)	1.000000
X(4)	30171.00
X(5)	1.000000
Y(1)	0.000000
Y(2)	1.000000
Y(3)	0.000000
Y(4)	0.000000
Y(5)	0.000000
S(1)	0.000000

Row	Slack or Surplus
1	2.568060
2	-0.2727273E-04
3	0.000000
4	0.1000000
5	1.660000
6	2.000000
7	0.4100000
8	9.666667
9	62.33333

APPENDIX B.2. Lingo input & output for MHE selection by using AUGMECON: Initial weight

```
SETS:
DECISION/1..5/:X;
BINARY/1..5/:Y;
DEVIATION/1/:s;
ENDSETS

DATA:
!Maintenanace cost;
MC1=19;
MC2=24.32;
MC3=9.55;
MC4=10.68;
MC5=10.68;
!Operating cost;
OC1=0.025;
OC2=0.037;
OC3=0.027;
OC4=0.028;
OC5=0.028;
!Purchase cost;
P1=15000;
P2=20000;
P3=8200;
P4=10000;
P5=18000;
!Salvage value;
S1=8500;
S2=10000;
S3=3800;
S4=4800;
S5=6700;
!Expected life;
F=1584;
!Weight;
W1=0.55451;
W2=0.57783;
W3=0.47101;
W4=0.57979;
W5=0.60742;
!Lift height;
h1=3.035;
h2=3.310;
h3=0.235;
h4=4.4;
h5=4.76;
!width of MHE;
b1=1.14;
b2=1.14;
b3=1.14;
b4=1.14;
b5=1.14;
!Load capacity;
E1=6;
E2=4;
E3=8;
E4=5;
E5=4;
!Stacking Aisle;
```

```
A1=3.39;
A2=2.7;
A3=2.247;
A4=2.779;
A5=3.12;
H=2.9;
L=2.8;
TH=480;
DST=42;
DSH=58;
Emax=2;
ENDDATA

MIN=(1-W1)*Emax*X(1)*Y(1)+(1-W2)*Emax*X(2)*Y(2)+(1-
W3)*Emax*X(3)*Y(3)+(1-W4)*Emax*X(4)*Y(4)+(1-
W5)*Emax*X(5)*Y(5)+0.00001*s(1)/0.00079;
X(1)*Y(1)*(P1-
S1)/F+X(1)*Y(1)*MC1+1346.8*OC1*Y(1)/X(1)+X(2)*Y(2)*(P2-
S2)/F+X(2)*Y(2)*MC2+1411*OC1*Y(2)/X(2)+X(3)*Y(3)*(P3-
S3)/F+X(3)*Y(3)*MC3+1484.4*OC3*Y(3)/X(3)+X(4)*Y(4)*(P4-
S4)/F+X(4)*Y(4)*MC4+1980.6*OC1*Y(4)/X(4)+X(5)*Y(5)*(P5-
S5)/F+X(5)*Y(5)*MC5+2330*OC1*Y(5)/X(5)+s(1)=103.6577;

Y(1)+Y(2)+Y(3)+Y(4)+Y(5)=1;

Y(1)*A1+Y(2)*A2+Y(3)*A3+Y(4)*A4+Y(5)*A5<=L;

Y(1)*b1+Y(2)*b2+Y(3)*b3+Y(4)*b4+Y(5)*b5<=L;

Y(1)*E1+Y(2)*E2+Y(3)*E3+Y(4)*E4+Y(5)*E5>=Emax;

h1*Y(1)+h2*Y(2)+h3*Y(3)+h4*Y(4)+h5*Y(5)>=H;

(1346.8/X(1))*Y(1)+(1411/X(2))*Y(2)+(1484.4/X(3))*Y(3)+(1980.6/X(4))
*Y(4)+(2330/X(5))*Y(5)<=480;
408<=(1346.8/X(1))*Y(1)+(1411/X(2))*Y(2)+(1484.4/X(3))*Y(3)+(1980.6/
X(4))*Y(4)+(2330/X(5))*Y(5);

@FOR(BINARY:@BIN(Y));@FOR(DECISION:@GIN(X));
END
```

Linearization components added:
Constraints: 120
Variables: 30

Objective value:	2.533020
Objective bound:	2.533020
Infeasibilities:	0.2727273E-04
Extended solver steps:	11
Total solver iterations:	840

Variable	Value
MC1	19.00000
MC2	24.32000
MC3	9.550000
MC4	10.68000
MC5	10.68000
OC1	0.2500000E-01
OC2	0.3700000E-01
OC3	0.2700000E-01
OC4	0.2800000E-01
OC5	0.2800000E-01
P1	15000.00
P2	20000.00
P3	8200.000
P4	10000.00
P5	18000.00
S1	8500.000
S2	10000.00
S3	3800.000
S4	4800.000
S5	6700.000
F	1584.000
W1	0.5545100
W2	0.5778300
W3	0.4710100
W4	0.5797900
W5	0.6074200
H1	3.035000
H2	3.310000
H3	0.2350000
H4	4.400000
H5	4.760000
B1	1.140000
B2	1.140000
B3	1.140000

B4	1.140000
B5	1.140000
E1	6.000000
E2	4.000000
E3	8.000000
E4	5.000000
E5	4.000000
A1	3.390000
A2	2.700000
A3	2.247000
A4	2.779000
A5	3.120000
H	2.900000
L	2.800000
TH	480.0000
DST	42.00000
DSH	58.00000
EMAX	2.000000
X(1)	1.000000
X(2)	3.000000
X(3)	1.000000
X(4)	29538.00
X(5)	1.000000
Y(1)	0.000000
Y(2)	1.000000
Y(3)	0.000000
Y(4)	0.000000
Y(5)	0.000000
S(1)	0.000000

Row	Slack or Surplus
1	2.533020
2	-0.2727273E-04
3	0.000000
4	0.1000000
5	1.660000
6	2.000000
7	0.4100000
8	9.666667
9	62.33333