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16. Abstract

This report summarized the research conducted at the University of Texas on the performance analysis of priority systems for containers. The performance analysis focused on a selected group of possible priority systems that differ in the extent in which service by priority is implemented. The systems analyzed are: a) base case, i.e., no service differentiation; b) "hot hatch" programs; c) service differentiation at the storage yard; d) service differentiation at the yard gate and e) combinations of systems b), c), d). The performance analysis was conducted using a simulation system specially designed to simulate priority systems. The performance of these systems is assessed for different combinations of the relevant experimental factors, namely: a) operational scheme, b) proportion of high priority containers, and c) number of incoming containers. Using the resulting performance measures, the impacts on the different segments of users are assessed for each of the systems. In order to gain insights into the applicability of priority systems, i.e., their optimality from the decision maker's standpoint, a formulation was developed to determine under what range of parameters of a choice function a given alternative is optimal. The formulation developed was found to provide useful insights and revealed that all the systems considered have a range of conditions under which they are optimal. Finally, the policy implications are analyzed and conclusions are drawn.

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RANGE OF APPLICABILITY OF PRIORITY SYSTEMS

by

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Research Report SWUTC/97/467304-2

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EXECUTIVE SUMMARY

This report summarizes the research conducted at The University of Texas at Austin on the range of applicability of priority systems. First, the experiment design is defined. Then, the results of the performance analysis conducted on a number of possible priority systems are summarized. For a full description of the results corresponding to the performance analysis, the reader is referred to the report entitled "On the Performance Analysis of Priority Systems." Finally, the range of applicability is determined. The systems analyzed are: (a) base case, in which high priority containers and low priority containers are randomly located on the ship and the service characteristics are the same, regardless of priority; (b) the existing "hot hatch programs," in which high priority containers are located on the hatches to be unloaded first; (c) service differentiation at the storage yard, in which high priority containers are sent to a special of the storage yard where they receive a faster service; (d) service differentiation at the yard gate, in which the trucks that come to pick up high priority containers receive expedited treatment; and (e) combinations of systems (b), (c) and (d). The performance of these systems is assessed for a number of different combinations of the relevant factors in terms of waiting times, operating costs and user costs. The computation experiment uses three different experiment factors, namely: (a) operational scheme, (b) proportion of high priority containers, and (c) number of incoming containers. Using the resulting performance measures, the impacts on the different segments users are assessed for each of the systems. In order to gain insights into the applicability of priority systems, i.e., their optimality from the decision maker's standpoint, a formulation was developed to determine under what range of parameters of a choice function a given alternative is optimal. The formulation developed was found to provide useful insights and revealed that all the systems have a range of conditions under which they are optimal. Finally, the policy implications are analyzed and conclusions are drawn.

ABSTRACT

This report summarizes the research conducted at The University of Texas at Austin on the range of applicability of priority systems for containers. The analysis focused on a selected group of possible priority systems that differ in the extent in which service differentiation by priority is implemented. The systems analyzed are: (a) base case, i.e., no service differentiation; (b) "hot hatch" programs; (c) service differentiation at the storage yard; (d) service at the yard gate; and (e) combinations of systems (b), (c) and (d). The performance analysis was conducted using a simulation system specially designed to simulate priority systems. The performance of these systems is assessed for different combinations of the relevant experimental factors, namely: (a) operational scheme, (b) proportion of high priority containers, and (c) number of incoming containers. Using the resulting performance measures, the impacts on the different segments of users are assessed for each of the systems. In order to gain insights into the applicability of priority systems, i.e., their optimality from the decision maker's standpoint, a formulation was developed to determine under what range of parameters of a choice function a given alternative is optimal. The formulation developed was found to provide useful insights and revealed that all the systems considered have a range of conditions under which they are optimal. Finally, the policy implications are analyzed and conclusions are drawn.

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INTRODUCTION

The success of containerization is due to the benefits associated with reducing a potentially infinite number of shapes and sizes of cargoes into a much smaller set of standard units, i.e., containers. By using containers, operators are able to take advantage of scale economies in a number of ways. First, the container is used as a consolidation unit that accommodates a batch of cargoes in one move. Second, and more importantly, since all containers can be handled in a similar manner (as boxes), operators can make efficient use of loading equipment and storage space. Without a doubt, the container-as-boxes approach has worked, but there are signs that indicate that this approach does not fit the needs of some segments of users. This is a fairly new situation, brought about by changes in the international economy that, among other impacts, have stressed the importance of considering the cargo value, which, in its broadest definition, includes both the intrinsic value of the cargo (determined by market value and replacement costs) and the logistic value of the cargo (a dynamic component that is a function of the importance of the cargo in the production system at particular times and at particular inventory levels).

In the last twenty years, developments in electronics and computer control have increasingly allowed production of goods with higher added value, smaller unit size and relatively low volume. In addition, globalization of the world economy has stressed the role of transportation and logistics as the key factors in reducing inventory costs. Concurrently, the growing popularity of Just-in-Time (JIT) production systems has increased the importance of the logistic value of cargoes. As a consequence, there is an increased need to expedite the flow of high-valued goods.

On the other hand, the advent of intermodalism has provided container carriers with the opportunity to target non-traditional markets. As part of these efforts, container carriers are trying to attract low-valued cargoes as a way to reduce the number of empty movements, e.g., cotton movements from Texas to the West Coast. If these attempts to attract low-valued cargoes succeed, container carriers and intermodal terminals may be handling, in the near future, a potentially high number of containers carrying low-valued cargoes.

The combined effect of the aforementioned trends is to increase the relative importance of both ends of the cargo value distribution. In this situation, an operational policy that does not distinguish containers according to cargo value is likely to penalize the segments of users located at both extremes of the cargo value distribution (i.e., the low-valued cargoes may be charged for a service that they do not need, and the high-valued cargoes may receive a quality of service below their needs). Container carriers have responded to this new challenge by implementing simple versions of priority systems (PS). In most of the cases, these PS consist of one or two ship hatches as "hot hatches," i.e., the ones to be unloaded first. So far, most of the "hot hatches" programs have been implemented for only Asia-US East Coast routes. However, it is expected that their use will be extended to other routes as soon as market conditions indicate prioritization needs.

PS can be implemented at the network level (i.e., by routing high priority containers through the fastest routes or by using the fastest modes within a given transportation network) and at the port level, i.e., by using alternative operational schemes. The relative importance of each of these levels will depend on the particular conditions of the problem.

The purpose of this research is to analyze the implementation of priority handling systems for containers at the port level. The aim of such systems is to expedite the flow of high-priority cargoes, thereby reducing user inventory costs. This "prime service" could be implemented through a combination of handling equipment, electronic data interchange technology, and innovative operational rules.

The possible PS range from the current "hot hatch" programs, in which service differentiation only occurs at the unloading stage, to more complex systems in which service differentiation is done at all the stages (i.e., movement to storage yard, storing yard operations, gate processing in/out of the storage yard and container retrieval). The analysis of the envisioned systems requires the examination of different aspects of the problem, including the performance analysis of different operational rules, the definition of pricing rules, and the corresponding information system and information technology (IS/IT).

This report discusses the range of applicability of the envisioned systems. The report has two main chapters. The first chapter describes the experiment design and the experimental factor for the computation experiment. Chapter II focuses on summarizing the results corresponding to the performance analysis, and on presenting the general formulation developed to determine the range of applicability.

Other reports that have been published as part of this research project are:

(a) "A Categorized and Annotated Bibliography to the Performance Analysis of Port Operations,"

(b) "Prior, a Computer System for the Simulation of Port Operations Considering Priorities,"

(c) "The Calibration of Prior, a Computer System for the Simulation of Port Operations Considering Priorities,"

(d) "The Role of Information Technology on the Implementation of Priority Systems and the State of the practice of Information Technology on Marine Container Terminals,"

(e) "On the Performance Analysis of Priority Systems,"

(f) "Range of Applicability of Priority Systems."

CHAPTER I. EXPERIMENT DESIGN

QUESTIONS ADDRESSED AND PERFORMANCE MEASURES

The questions addressed by this research revolved around a basic one: What are the technological and economic implications of implementing priority systems at the port level?. Answering this question required the implementation of a simulation system that provided estimates of the performance measures more directly related to the operator's decision criteria. In addition, the simulation system provided information about the quality of the service, i.e., the customer's perspective, because one of the basic assumptions of this research is that the operators are sensitive to the customer's perspective of the problem.

From the operator standpoint, the most relevant decision criteria are: (a) operating costs and profitability which are highly determined by the level of equipment utilization and efficiency and (b) risk of non-compliance, which is determined by service reliability. From the customer standpoint, the most important criterion is reliability, i.e., the probability that their containers are ready to be retrieved when scheduled. Both aspects were assessed by using three set of performance measures: (a) waiting and service times for the different service stages, which provided the basic input for the cost calculations; (b) equipment utilization indicators, e.g., percentage of time being idle; and, (c) the probability the containers are ready to be retrieved when the customers needs them, i.e., the customer side of the problem.

The simulation system provides a multidimensional output that includes: (a) detailed information about individual servers, e.g., mean and standard deviations of service, waiting, breakdown and repositioning times; (b) server statistics, e.g., percentage of total time being idle, busy, repositioning, broken or waiting; and (c) cross statistics, e.g., matrices of mean waiting times of gantry cranes waiting for yard trucks.

A printout of the full output produced by the simulation system requires, on average, thirty (30) pages per ship. Since the number of observations (ships) have been set to twenty (20), the output file for one case would have 600 pages. Thus, the analysis of the 24 different cases considered in the experiment design would require to print an output 14,400 pages long.

For obvious reasons, it is required to find a way to collapse the output into a small set of summarizing performance indicators for which the analysis can be reduced to a manageable size. In order to provide an adequate description of system performance, the selected indicators must be able to distinguish: (a) between service and waiting times and (b) between unloading and retrieval process. Thus, it was decided that the following performance indicators would be used:[1]

(a) Service times at unloading, equal to the summation of the average service times of the different stages comprising the unloading process, namely, unloading from the ship, movement to the storage yard and unloading at the yard.

(b) Waiting times at unloading, same as (a) for waiting times.

(c) Service times at retrieval, equal to the summation of the average service times of the different stages comprising the retrieval process, namely, service at the "in" gate, movement to the yard, loading at the yard, movement to the gate, and service at the "out" gate.

(d) Waiting times at retrieval, same as (d) for waiting times.

In addition to the performance indicators defined above, which are mainly related to system performance, there are two important aspects to be considered: service reliability and operating costs. The former is important for port users while the latter is for port managers. The performance indicators that will be used to capture these aspects are:

(e) Mean slack times that are equal to the time elapsed between the moment in which the container is ready to be picked up and the time in which the corresponding external truck arrives to retrieve it.

(f) Reliability, equal to the probability of having positive slack times.

(g) Operating costs which are an estimate of the amount of resources used. The operating costs are the output of the program in charge of post-processing the simulation system's output.

The performance of the different alternative systems is analyzed using these criteria. It is expected that the selected indicators provide a full picture of the various impacts of the systems under analysis.

Before discussing the results, it is important to highlight the scope and limitations of the simulation system. First, the objective of this modelling effort is to simulate a typical operation, rather than to simulate the operation of a specific terminal. For that reason, the results provided here have no relation to the different terminals that, generously, provided data for this research.

Second, port operations involves a dynamic decision making process in which the terminal manager continuously monitors system performance and takes decisions accordingly. By virtue of this process, the terminal manager tries to optimize their operations at each level of demand. The way in which the goal of optimizing operations is achieved is highly dependent on

[1] The underlining represents the name assigned to each performance indicator.

the experience of the terminal manager, and on the practices and tradition of the company. Since modelling this decision making process is beyond the scope of this research, the different systems were simulated with a fixed combination of equipment. In this context, the simulation results will only provide an indication of relative performance.

Third, the interaction between supply and demand was not considered. Specifically, dwelling times are likely to be determined by the total demand and the storage pricing policy. In this context, a growing demand may require the implementation of storage charges so that the storage yard will not be overfilled. External trucks arriving to retrieve containers are likely to take into consideration the level of service they perceive. If the waiting times are high, for instance, some truck drivers are going to change their arrivals to avoid peak periods of congestion at the terminal. Since the distributions of container dwelling times were assumed to be the same, regardless of the level of demand, waiting times are likely to be overestimated. This limitation must be understood as the consequence of having neither adequate theory nor data to model this problem.

EXPERIMENTAL FACTORS

Three different factors were considered in the numerical experiments. The experimental factors can be classified in the following two categories:

a) Operational factors:

Operational policy (six different policies)

b) Demand factors:

Proportion of high priority containers (25% and 50%)

Total demand (1,000 containers/week and 2,000 containers/week)

The operational policy defines the extent to which service differentiation by priority is implemented. Figure 1.1 shows the characteristics of the operational policies considered. As can be seen, an incomplete factorial design was used (a full factorial design would have required the simulation of eight different operational policies). An incomplete factorial design was chosen to keep the computational cost down while focusing the analysis on the operational policies of highest practical value (i.e., that usually involves hot hatches and increasing levels of service differentiation).

Base case: No priority system implemented. High and low priority containers are located randomly on the ship. The unloading process does not consider service differentiation by priority.

Priority system I -Service differentiation at the unloading from the ship- (PS-I): The location of the containers on the ship is priority dependent. The gantry cranes unload the high priority containers first. Though there might be a number of possible variations for this type of system the most important to be considered, from a practical standpoint, is the "hot hatch" system. In this case all high priority containers are located on the priority hatches allowing the gantry cranes to unload them with a minimum number of lateral movements.

Priority system II -Service differentiation at the storage yard- (PS-II): The high priority containers are sent to special lots where they receive a faster service. There are a number of different alternative systems that could have been analyzed. Some of the possible variations were: (a) storing the high priority containers on chassis (wheeled operations, stacking height equal to one) and (b) assigning more yard cranes to service the lots where the high priority containers are stored (stacking height greater than one). Since the basic postulate of this research is that high priority containers demand a level of service significantly different than the one provided to low priority containers, the analysis focused on alternative (a) because it provided a maximum level of service differentiation. In all cases low priority containers are stacked three or four high, to compensate for the additional space required by the storing of high priority containers.

Priority system III -Service differentiation at the yard gate- (PS-III): The trucks arriving to pick up high priority containers receive a faster service at the gate. Currently, there are a number of implementations of electronic data interchange technology (EDI), information technology that can be adapted to this purpose. Some of these implementations use cameras to retrieve information about the truck identification, electronic transponders to verify the identification of the containers and computers to do the paper work.

Priority system IV (PS-I-II): Combination of PS-I and PS-II.

Priority system V (PS-I-II-III): Combination of PS-I, PS-II and PS-III.

Figure 1.1: Description of operational policies

	Location of HPCs	Yard crane operations	Yard gate operations
Base case	Random	No priority service HPC stacked as other containers	No priority service
Priority system I	Hot hatches	No priority service HPC stacked as other containers	No priority service
Priority system II	Random	HPC are wheeled	No priority service
Priority system III	Random	No priority service HPC stacked as other containers	HPC receive preferential service
Priority system IV (I + II)	Hot hatches	HPC are wheeled	No priority service
Priority system V (I+II+III)	Hot hatches	HPC are wheeled	HPC receive preferential service

The yard crane allocation scheme defines the way in which the work at the storage yard is distributed among the yard cranes. Two cases were implemented in the simulation system, namely, static and dynamic. In the static allocation scheme, at the beginning of the simulation, the yard lots are distributed among the yard cranes. The allocation does not change during the simulation and, regardless of the queues, yard cranes are not allowed to cooperate with each other. On the other hand, when dynamic allocation is used, the allocation is revised at a time interval specified by the user. Yard cranes collaborate with each other to tackle the longest queue. Since in practice static allocation is hardly used, all the runs were performed using dynamic allocation.

Two priority classes were considered, high and low. The former represented containers carrying high valued cargoes, i.e., from the user's perspective. Conversely, the latter represented containers carrying low-valued cargoes. Two different proportions of high priority containers were used, 25% and 50%. These values were selected for practical, and probably arbitrary, reasons. First, it was considered that if the majority of the containers handled at a given port are "high priority containers," then it is very likely that the current definition of "high priority" is not appropriate. If the majority of containers requires the special treatment reserved for high priority containers, then this treatment can not be considered "special." For that reason, 50% was selected as the upper bound. 25% was selected because it is the mid-value between 0% and 50%. The second demand factor considered is the total demand. Two values were considered: 1,000 containers/week and 2,000 containers/week. The latter was estimated as the capacity of the terminal being simulated.

CHAPTER II. SUMMARY OF RESULTS AND RANGE OF APPLICABILITY

This chapter summarizes the simulation results and defines the range of applicability of the systems. In the first section, the results are summarized and compared in order to gain insight into the comparative advantages of the different systems. The remainder of the chapter focuses on presenting the general framework to estimate the range of applicability. Some examples are given and finally, the proposed approach is applied to the simulation output.

SUMMARY OF RESULTS

This section focuses on summarizing and comparing the results corresponding to the different test cases. To facilitate the analysis and interpretation of results, the performance measures were normalized by dividing them by the corresponding maximum value. It was also decided to use "probability of non-compliance" instead of "system reliability" in order to have decreasing monotonic preferences in all the decision variables.

The results corresponding to high priority containers, reveal some general characteristics:

1. The implementation of priority systems, as expected, most significantly impact the performance measures associated with high priority containers. In some cases, these performance measures drop to less than 10% of the values corresponding to the base case.
2. Overall, the systems that articulate service differentiation at various stages[2] (i.e., PS-IV and PS-V) produced the largest impact on the performance of high priority containers, by modifying several performance measures at the same time. This seems to suggest the existence of strong interaction effects among the different service processes.
3. On the other hand, the priority systems in which service differentiation is implemented at only one stage [3] (i.e.,"hot hatch," "priority at the storage yard" and "priority at the gates") tend to have a narrower impact on the performance measures. At most, two performance measures are significantly modified each time. The impact of the implementation of each of the single-stage systems can be summarized as follows:

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[2] From now on, these systems will be referred to as "articulated."
[3] From now on, these systems will be referred to as "single-stage."

PS-I (hot hatches) most significantly affects waiting times at unloading and probability of non-compliance. The former drops to 74%-86% of the base case values and the latter to 14%-63% of the base case values.

PS-II (priority at the storage yard) affects waiting times at retrieval and service time at unloading. Waiting time at retrieval drops to 9%-34% of the base case values while service time at unloading becomes approximately 50% of the base case value.

PS-III (priority operations at the gates) is the single most important factor in reducing service time at retrieval which becomes 16% of the base case value. An unfortunate consequence of the increased efficiency at the gates is that the probability of non-compliance increases.[4] This phenomenon stresses the importance of articulating service differentiation at various stages.

4. The performance measures associated with high priority containers tend to deteriorate as the number of incoming high priority containers increases, which is due to the increased workload at the servers handling high priority containers.

The results corresponding to low priority containers have the following general characteristics:

1. The implementation of "hot hatch" systems slightly deteriorates the performance of low priority containers. The most significant impact being on waiting times at unloading that increase on average 10%.
2. The performance measures associated with low priority containers improve as the number of incoming high priority containers increases. Since the total number of incoming containers has been assumed to be constant, an increased flow of high priority containers implies a reduced flow of low priority containers. This, in turn, improves the corresponding performance measures.

Finally, in order to reduce the number of decision criteria, the service times were added to the corresponding waiting times. The resulting total times, at unloading and at retrieval, will be used in conjunction with total unit cost and probability of non-compliance to determine the range of applicability of the different systems. Table 2.1 shows the resulting multicriteria decision matrix that is the input to the formulation proposed in the next section.

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[4] Attributed to the use of automatic equipment identification (AEI) devices.

Table 2.1: Multicriteria decision matrix

Case A: 25% high priority containers, 1,000 containers/week

	Priority 1				Priority 2			
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
System:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
a. Base Case	0.988	0.906	0.931	1.000	0.911	0.931	1.000	0.983
b. Hot hatch	0.741	1.000	0.135	0.971	1.000	0.964	0.934	1.000
c. Storage yard	0.900	0.147	0.629	0.655	0.859	0.977	0.982	0.913
d. Terminal gates	1.000	0.918	1.000	0.816	0.920	0.944	0.879	0.977
e. All but gates	0.656	0.122	0.064	0.648	0.922	1.000	0.907	0.895
f. All	0.657	0.008	0.080	0.440	0.928	0.986	0.948	0.901

Case B: 25% high priority containers, 2,000 containers/week

	Priority 1				Priority 2			
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
System:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
a. Base case	1.000	0.839	0.997	1.000	0.925	0.951	0.865	0.985
b. Hot hatch	0.735	1.000	0.624	0.958	1.000	0.990	1.000	1.000
c. Storage yard	0.918	0.078	0.906	0.656	0.866	1.000	0.807	0.904
d. Terminal gates	0.998	0.846	1.000	0.789	0.926	0.939	0.892	0.973
e. All but gates	0.682	0.154	0.533	0.653	0.934	1.000	0.842	0.887
f. All	0.665	0.003	0.511	0.431	0.935	0.999	0.921	0.899

Case C: 50% high priority containers, 1,000 containers/week

	Priority 1				Priority 2			
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
System:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
a. Base Case	0.976	0.985	0.881	1.000	0.875	0.941	0.921	0.961
b. Hot hatch	0.862	1.000	0.675	0.973	1.000	0.991	1.000	1.000
c. Storage yard	0.863	0.456	0.507	0.644	0.811	0.995	0.887	0.830
d. Terminal gates	1.000	0.957	1.000	0.797	0.887	0.947	0.891	0.946
e. All but gates	0.741	0.455	0.339	0.643	0.908	1.000	0.925	0.831
f. All	0.754	0.005	0.395	0.426	0.908	0.995	0.896	0.836

Case D: 50% high priority containers, 2,000 containers/week

	Priority 1				Priority 2			
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
System:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
a. Base Case	1.000	0.973	0.775	1.000	0.882	0.913	0.863	0.972
b. Hot hatch	0.863	1.000	0.629	0.958	1.000	0.989	1.000	1.000
c. Storage yard	0.904	0.346	0.659	0.643	0.814	0.993	0.808	0.838
d. Terminal gates	0.999	0.887	1.000	0.779	0.878	0.914	0.852	0.942
e. All but gates	0.780	0.350	0.524	0.642	0.918	1.000	0.911	0.809
f. All	0.791	0.002	0.752	0.424	0.918	0.997	0.926	0.810

GENERAL FORMULATION

In general terms, "range of applicability" refers to the set of conditions under which a given alternative is an "attractive" option. Though intuitive, the aforementioned definition is too general because it does not define what is an "attractive" option. In the strictest sense, the determination of the range of applicability requires quantitative knowledge about the characteristics of the demand and the characteristics of the decision making process. The lack of knowledge about the demand and its economic characteristics prevents the quantification of the economic benefits, external costs, and consequently, a formal feasibility analysis. Additionally, not knowing the behavioral characteristics of the multicriteria decision making process that takes place prevents a formal application of multicriteria decision making models. The assessment of the preference structure of the decision maker, including the weights of importance associated to each criterion, would require interviewing the decision maker(s), e.g., the terminal manager, and doing this is beyond the scope of this research.

To overcome this limitation, an alternative concept, "range of optimality," will be used. The approach used to estimate the range of applicability by means of the range of optimality consists of assuming a choice function and then obtaining the range of values of the parameters for which a given alternative is the preferred option. Since these parameters have a behavioral interpretation, the analysis will provide insight into the applicability of the different systems and its relationship with the decision making process. The range of optimality is intended to provide an estimate of the range of applicability that will be valid depending upon the consistency of the assumed choice function with respect to the true preference structure of the decision maker. The summary of performance measures presented in the previous section provides the background information for the decision making process. In mathematical terms:[5]

A_n = Choice set of feasible and non-dominated alternatives

$x = \{x_1, x_2, \ldots\ldots x_m\}$ = Vector of decision criteria

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots\cdots & c_{1m} \\ c_{21} & c_{22} & \cdots & c_{2m} \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot \\ c_{n1} & c_{n2} & \cdots & c_{nm} \end{bmatrix} = \begin{bmatrix} c^1 \\ c^2 \\ \cdots \\ c^n \end{bmatrix} = \text{Decision matrix}$$

c^i = Row vector containing performance of alternative i with respect to x.

l = Column vector containing the parameters of the choice function

[5] Lowercase will denote vectors and scalars, while uppercase will denote matrices.

$$\Lambda = \left\{ \lambda : 0 \le \lambda_k \le 1, \sum_{k=1}^{m} \lambda_k = 1 \right\} = \text{Set of feasible l's} \tag{1}$$

$$\Omega(i) = \left\{ f(c^i, \lambda) \ \rangle \ f(c^l, \lambda) \right\}, \forall l \ne i, \forall \lambda_k \in \Lambda = \text{Choice function} \tag{2}$$

Where:

$f(c^i, \lambda) =$ Function representing the decision maker's preference structure

$\rangle$ is the dominance operator "preferred to"

$\approx$ is the indifference operator, and

$\langle$ is the operator "not preferred to"

The range of optimality for a given alternative i can be determined by solving for the vector of parameters λ_*^j in the following (n-1) decision problems:

1) Find λ_*^1 such that:

$$f(c^i, \lambda_*^1) \approx f(c^1, \lambda_*^1), \forall \lambda_k \in \Lambda \tag{3}$$

$$f(c^i, \lambda_*^1) \ \rangle \ f(c^l, \lambda_*^1), \forall l \ne i, l \ne 1, \forall \lambda_k \in \Lambda \tag{4}$$

2) Find λ_*^2 such that:

$$f(c^i, \lambda_*^2) \approx f(c^2, \lambda_*^2), \forall \lambda_k \in \Lambda \tag{5}$$

$$f(c^i, \lambda_*^2) \ \rangle \ f(c^l, \lambda_*^2), \forall l \ne i, l \ne 2, \forall \lambda_k \in \Lambda \tag{6}$$

...

n-1) Find λ_*^{n-1} such that:

$$f(c^i, \lambda_*^{n-1}) \approx f(c^{n-1}, \lambda_*^{n-1}), \forall \lambda_k \in \Lambda \tag{7}$$

$$f(c^i, \lambda_*^{n-1}) \ \rangle \ f(c^l, \lambda_*^{n-1}), \forall l \ne i, l \ne n-1, \forall \lambda_k \in \Lambda \tag{8}$$

Where:

$\lambda_*^j =$ Vector of solutions to problem j

The set of solutions, $\lambda_*^j, \forall j = 1, n-1$, to these decision problems defines the region of L for which alternative i is the preferred alternative. There will be instances in which some of the problems will not have a feasible solution. However, if the alternatives are non-dominated, the non-feasibility of some of the problems should not be a cause for concern because the region of optimality will be defined by the solution to the remaining problems.

IMPLEMENTATION OF PROPOSED APPROACH

The formulation presented in the previous section does not make any assumptions about the decision maker's preference structure or the choice function. There is a wide variety of potential choice functions that differ in the nature of the underlying assumptions. However, since there is no information about the characteristics of the decision maker's preference structure, there is no way to determine which preference structure function is the most appropriate and consequently, a simple choice function will be used. It will be assumed that the decision maker(s) make decisions by optimizing a convex combination of the decision criteria. As it shall be seen, the most significant advantage of making this assumption is that it allows to use linear programming (LP) formulations.

Thus, the choice function can be represented as:

$$z_i = c^i \lambda \tag{9}$$

Using equation (9) the set of decision problems given by equations (3) to (8) can be reformulated as follows: [6]

Problem j:

$$MIN\ z_i = c^i \lambda \tag{10}$$

subject to:

$$c^i \lambda = c^j \lambda, \forall \lambda_k \in \Lambda \tag{11}$$

$$c^i \lambda \le c^l \lambda, \forall l \ne i, l \ne j, \forall \lambda_k \in \Lambda \tag{12}$$

This problem, in turn, can be reformulated as:

Problem j:

$$MIN\ z_i = c^i \lambda \tag{13}$$

subject to:

$$\left(c^i - c^j\right)\lambda = 0, \forall \lambda_k \in \Lambda \tag{14}$$

$$\left(c^l - c^i\right)\lambda \ge 0, \forall l \ne i, l \ne j, \forall \lambda_k \in \Lambda \tag{15}$$

The region of optimality for alternative i will be characterized by the set of solutions i.e., $\lambda_*^j, \forall j = 1, n-1$, to these decision problems. All $\binom{n-1}{2}$ convex combinations of λ_*^j will preserve the optimality of alternative i and consequently, they will define the region of Λ in which alternative i is the preferred one.

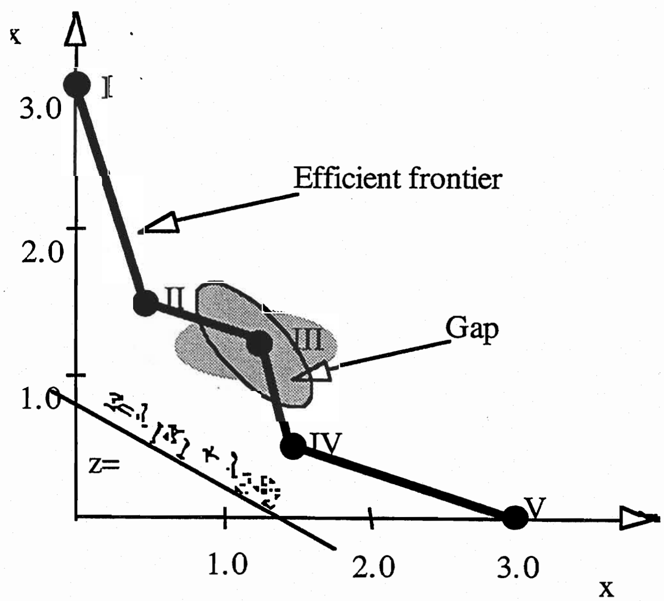
In addition to the set of solutions λ_*^j, it may happen that alternative i is optimal according to a uni-dimensional optimization of one or more than one decision criteria. In such a case, these points will also characterize the region of optimality of alternative i and consequently they must be included. The coefficient of the optimizing decision criterion will be equal to one while the rest of coefficients are equal to zero. Since determining the existence of these points is relatively easy (only a quick examination of the decision matrix C is needed) no attempt was made to develop a mathematical formulation to obtain them. To refer to these points, the notation λ_{01}^k will be used, where k is the index of the optimizing decision criterion.

---

[6] Only a typical problem j is shown.

A limitation of using a convex combination of the decision criteria as the choice function is that the resulting model is not able to deal properly with duality gap. Duality gap is the condition that arises when the primal and the dual have different solutions. In vector optimization problems, a non-convex efficient frontier usually produces duality gap, (see Figure 2.1). In such a case, there is no a combination of weights for which alternative III is the preferred option. This condition will be further explored in the second example of the next section.

Figure 2.1: Example of non-convex efficient frontier



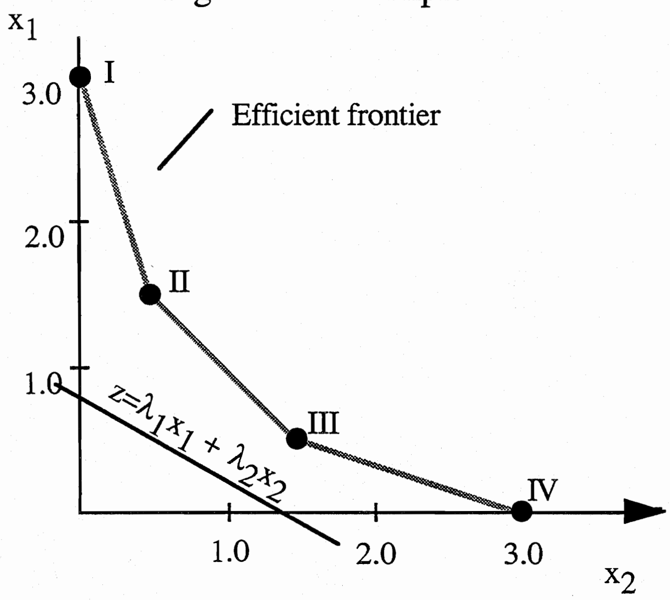
The reader who is familiar with vector optimization techniques, will find some similarities between the proposed approach of Section 2.3 and the theory of multiparametric linear programming (MLP), first developed by Sokolová (SOKOLO68). Further contributions to MLP were made by Gal and Nedoma (GALNEDO72) and Zeleny (ZELENY74).

MLP expresses the solution of a linear programming problem as a function of the original set of coefficients and constraints, and a vector of parameters. The algorithm developed by Gal and Nedoma determines the parameters' range of values for which a given alternative is optimal. Gal and Nedoma recognize two different cases: the parametrization of the right hand side of the constraint set (MLP-RHS, for short) and the parametrization of the objective function coefficients (MLP-OFC). Although dealing with related problems, MLP-RHS and MLP-OFC are unable to

EXAMPLES

Consider the example shown in Figure 2.2 depicting the performance of four alternatives according to the decision criteria x_1 and x_2. As seen, the alternatives are non-dominated. To illustrate the approach, the range of optimality of alternative III will be determined using the formulation presented in section 2.3

Figure 2.2: Example #1



The decision matrix C is:

$$C = \begin{bmatrix} 0 & 3 \\ 0.5 & 1.5 \\ 1.5 & 0.5 \\ 3 & 0 \end{bmatrix} = \begin{bmatrix} c^{I} \\ c^{II} \\ c^{III} \\ c^{IV} \end{bmatrix} \quad (16)$$

The range of optimality for III is determined by the solution of the following problems:

<u>Problem 1:</u>

MIN $z_{III} = c^{III}\, l$ (17a)

subject to:

$z_{III} = z_{I}$ (18a)

$z_{III} \le z_{II}$ (19a)

$z_{III} \le z_{IV}$ (20a)

$l_1, l_2 \ge 0$ (21a)

$l_1 + l_2 = 1$ (22a)

Substituting x_1 and x_2 for the different alternatives, the problem can be transformed to:

$$\text{MIN } z_{III} = 1.5\, l_1 + 0.5\, l_2 \qquad (17b)$$

subject to:

$$(1.5 - 0.0)\, l_1 + (0.5 - 3.0)\, l_2 = 0 \qquad (18b)$$

$$(1.5 - 0.5)\, l_1 + (0.5 - 1.0)\, l_2 \leq 0 \qquad (19b)$$

$$(1.5 - 3.0)\, l_1 + (0.5 - 0.0)\, l_2 \leq 0 \qquad (20b)$$

$$l_1, l_2 \geq 0 \qquad (21b)$$

$$l_1 + l_2 = 1 \qquad (22b)$$

Similarly:

<u>Problem 2:</u>

$$\text{MIN } z_{III} = c^{III}\, l \qquad (23a)$$

subject to:

$$z_{III} = z_{II} \qquad (24a)$$

$$z_{III} \leq z_{I} \qquad (25a)$$

$$z_{III} \leq z_{IV} \qquad (26a)$$

$$l_1, l_2 \geq 0 \qquad (27a)$$

$$l_1 + l_2 = 1 \qquad (28a)$$

Thus,

$$\text{MIN } z_{III} = 1.5\, l_1 + 0.5\, l_2 \qquad (23b)$$

subject to:

$$(1.5 - 0.5)\, l_1 + (0.5 - 1.5)\, l_2 = 0 \qquad (24b)$$

$$(1.5 - 0.0)\, l_1 + (0.5 - 3.0)\, l_2 \leq 0 \qquad (25b)$$

$$(1.5 - 3.0)\, l_1 + (0.5 - 0.0)\, l_2 \leq 0 \qquad (26b)$$

$$l_1, l_2 \geq 0 \qquad (27b)$$

$$l_1 + l_2 = 1 \qquad (28b)$$

And, finally:

<u>Problem 3:</u>

$$\text{MIN } z_{III} = c^{III}\, l \qquad (29a)$$

subject to:

$$z_{III} = z_{IV} \qquad (30a)$$

$$z_{III} \leq z_{I} \qquad (31a)$$

$$z_{III} \leq z_{II} \qquad (32a)$$

$$l_1, l_2 \geq 0 \qquad (33a)$$

$$l_1 + l_2 = 1 \qquad (34a)$$

Thus,

$$\text{MIN } z_{III} = 1.5\, l_1 + 0.5\, l_2 \tag{29b}$$

subject to:

$$(1.5 - 3.0)\, l_1 + (0.5 - 0.0)\, l_2 = 0 \tag{30b}$$

$$(1.5 - 0.0)\, l_1 + (0.5 - 3.0)\, l_2 \leq 0 \tag{31b}$$

$$(1.5 - 0.5)\, l_1 + (0.5 - 1.5)\, l_2 \leq 0 \tag{32b}$$

$$l_1, l_2 \geq 0 \tag{33b}$$

$$l_1 + l_2 = 1 \tag{34b}$$

The solutions to problems 1 to 3 are summarized on Table 2.2

Table 2.2: Summary of solutions

Problem	$\lambda 1$	$\lambda 2$
#1	Not feasible	
#2	0.50	0.50
#3	0.25	0.75

Therefore, alternative III will be the preferred alternative as long as:

$$0.25 \leq l_1 \leq 0.50 \tag{35}$$

$$l_1 + l_2 = 1 \tag{36}$$

The process may be repeated for all alternatives. The range of optimality for all the alternatives is depicted in Table 2.3.

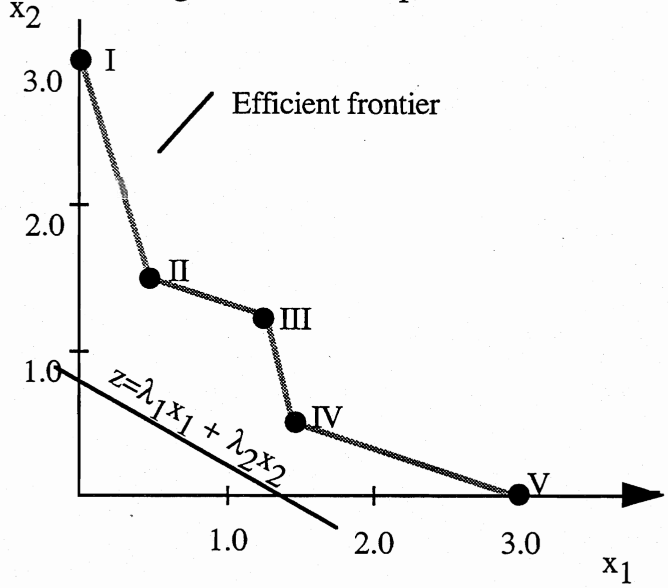
Table 2.3: Range of optimality

$\lambda 1$	Preferred alternative
$\lambda 1 > 0.75$	I
$\lambda 1 = 0.75$	I,II
$0.75 > \lambda 1 > 0.50$	II
$\lambda 1 = 0.50$	II,III
$0.50 > \lambda 1 > 0.25$	III
$\lambda 1 = 0.25$	III,IV
$\lambda 1 < 0.25$	V

$\lambda 1 + \lambda 2 = 1$

Consider now the example shown in Figure 2.3.

Figure 2.3: Example #2



As can be seen, there is a duality gap in the vicinity of alternative III.

The decision matrix C is:

$$C = \begin{bmatrix} 0 & 3 \\ .5 & 1.5 \\ 1.25 & 1.25 \\ 1.5 & 0.5 \\ 3 & 0 \end{bmatrix} = \begin{bmatrix} c^{I} \\ c^{II} \\ c^{III} \\ c^{IV} \\ c^{V} \end{bmatrix} \qquad (37)$$

An attempt to determine the range of optimality using a convex combination of decision criteria will result in the following:

<u>Problem 1:</u>

$\text{MIN } z_{III} = c^{III}\ l$ (38a)

subject to:

$z_{III} = z_{II}$ (39a)

$z_{III} \le z_{I}$ (40a)

$z_{III} \le z_{IV}$ (41a)

$z_{III} \le z_{V}$ (42a)

$l_1, l_2 \ge 0$ (43a)

$l_1 + l_2 = 1$ (44a)

Substituting x_1 and x_2 for the different alternatives, the problem can be transformed to:

$$\text{MIN } z_{III} = 1.25\, l_1 + 1.25\, l_2 \quad \text{(38b)}$$

subject to:

$$(1.25 - 0.5)\, l_1 + (1.25 - 1.5)\, l_2 = 0 \quad \text{(39b)}$$

$$(1.25 - 0.0)\, l_1 + (1.25 - 3.0)\, l_2 \leq 0 \quad \text{(40b)}$$

$$(1.25 - 1.5)\, l_1 + (1.25 - 0.5)\, l_2 \leq 0 \quad \text{(41b)}$$

$$(1.25 - 3.0)\, l_1 + (1.25 - 0.0)\, l_2 \leq 0 \quad \text{(42b)}$$

$$l_1, l_2 \geq 0 \quad \text{(43b)}$$

$$l_1 + l_2 = 1 \quad \text{(44b)}$$

Equations (39b) to (44b) imply that:

$$l_2 = 3.0\, l_1 \quad \text{(45)}$$

$$l_2 \leq 1.25/1.75\, l_1 \quad \text{(46)}$$

$$l_2 \leq 1/3\, l_1 \quad \text{(47)}$$

$$l_2 \leq 1.75/1.25\, l_1 \quad \text{(48)}$$

Since equations (44) to (48) cannot be simultaneously satisfied, the linear programming problem has no feasible solution. It must be highlighted that, far from being an extreme example, duality gap is very common in multicriteria decision making problems where the choice set is comprised of a finite set of alternatives. In such cases, the convex combination approach will fail to identify an alternative as belonging to the efficient frontier and consequently, the range of optimality -as defined in this research- does not exist. This must be understood as an unfortunate limitation of decision theory. As it shall be seen in the next sections, some of the systems simulated in this research exhibit duality gap, and consequently, there is no way to determine the range of optimality.

In the next section, this approach is used to determine the range of optimality i.e., range of applicability, of the different systems simulated in this research. In order to assure some consistency in assessing the relative importance of the different decision criteria, the scale shown in Table 2.4 was constructed. Though arbitrarily defined, the scale shown in Table 2.4 will aid in the conceptual analysis of the results.[7]

[7] In the strictest sense, the importance of a decision criterion is determined not only by the parameter λ, but by the scale of magnitude of the decision variable. However, for the sake of simplicity, it will be assumed that the importance of the decision criteria will be determined exclusively by the corresponding parameter λ.

Table 2.4: Intensity of importance		
Parameter:	Importance:	Notation:
λ = 0	No importance	0
0 < λ < 0.25	Weak importance	+
0.25 ≤ λ < 0.50	Essential importance	++
0.50 ≤ λ < 0.75	Very strong importance	+++
0.75 ≤ λ ≤ 1	Absolute importance	++++

RESULTS CORRESPONDING TO THE BASE CASE

The approach described in section 2.3 and summarized in equations (13) to (15) was applied to the base case. The region of optimality corresponding to the base case, characterized by the set of solutions, is shown in Table 2.5.

Table 2.5: Region of optimality for the base case

	Case A: 25% HPC, 1000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
Solution:	Time at unloading	Time at retrieval	Non compl.	Total cost	Time at unloading	Time at retrieval	Non compl.	Total cost
λ*1	0.000	0.000	0.053	0.000	0.191	0.756	0.000	0.000
λ*2	0.000	0.000	0.000	0.000	0.469	0.531	0.000	0.000
λ*3	0.000	0.000	0.000	0.000	0.414	0.501	0.085	0.000
λ*4	-	-	-	-	-	-	-	-
λ*5	0.000	0.000	0.048	0.000	0.298	0.654	0.000	0.000
λ01–6	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000

	Case B: 50% HPC, 1000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
Solution:	Time at unloading	Time at retrieval	Non compl.	Total cost	Time at unloading	Time at retrieval	Non compl.	Total cost
λ*1	-	-	-	-	-	-	-	-
λ*2	0.000	0.000	0.000	0.000	0.458	0.542	0.000	0.000
λ*3	0.000	0.000	0.000	0.000	0.297	0.487	0.216	0.000
λ*4	0.000	0.000	0.093	0.000	0.120	0.787	0.000	0.000
λ*5	0.000	0.003	0.091	0.000	0.116	0.790	0.000	0.000
λ01–6	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000

	Case C: 25% HPC, 2000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
Solution:	Time at unloading	Time at retrieval	Non compl.	Total cost	Time at unloading	Time at retrieval	Non compl.	Total cost
λ*1	-	-	-	-	-	-	-	-
λ*2	0.000	0.000	0.000	0.000	0.000	0.542	0.458	0.000
λ*3	0.000	0.000	0.000	0.017	0.000	0.588	0.395	0.000
λ*4	0.000	0.000	0.038	0.000	0.000	0.554	0.408	0.000
λ*5	-	-	-	-	-	-	-	-

	Case D: 50% HPC, 2000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
Solution:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
λ*1	-	-	-	-	-	-	-	-
λ*2	0.000	0.000	0.227	0.000	0.000	0.510	0.263	0.000
λ*3	0.000	0.000	0.025	0.000	0.000	0.419	0.556	0.000
λ*4	0.000	0.000	0.227	0.000	0.000	0.510	0.263	0.000
λ*5	0.000	0.067	0.107	0.000	0.000	0.739	0.087	0.000
λ01–6	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000

As can be seen in Table 2.5, the coefficients of the decision criteria associated with high priority containers (i.e., l_1, l_2, l_3 and l_4) are negligible. From the behavioral standpoint, these results imply that for the base case to be the preferred option, the decision maker must perceive that the level of service for high priority containers is of no importance. Conversely, the base case would be the preferred option if the decision maker(s) gives considerable importance to total time at unloading, total time at retrieval and the probability of non-compliance, while disregarding total unit costs for low priority containers.

Since not assigning any importance to the level of service associated with high priority containers is not very likely, it can be concluded that for the level of demand considered in this research the range of applicability of the base case is very limited. Of course, it must be highlighted that this conclusion is conditioned on the validity of the choice function, i.e., its consistency with the decision maker's preference structure.

RESULTS CORRESPONDING TO HOT HATCHES

The proposed approach was applied to the hot hatches. The results corresponding to the different test cases are summarized in Table 2.6. As can be seen in Table 2.6, the region of optimality for hot hatches is defined for only one case, i.e., 25% of high priority containers and 1,000 containers/week. The other three cases exhibited duality gap, making it impossible to determine the range of optimality.

Table 2.6: Region of optimality for the hot hatches								
	Case A: 25% HPC, 1000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
Solution:	Time at unloading	Time at retrieval	Non compl.	Total cost	Time at unloading	Time at retrieval	Non compl.	Total cost
λ*1	0.000	0.000	0.053	0.000	0.191	0.756	0.000	0.000
λ*2	-	-	-	-	-	-	-	-
λ*3	0.000	0.000	0.042	0.000	0.000	0.458	0.499	0.000
λ*4	0.000	0.000	0.275	0.000	0.000	0.621	0.105	0.000
λ*5	0.000	0.000	0.286	0.000	0.000	0.714	0.000	0.000

Note: The existence of duality gap prevented to find solutions to the other cases

According to Table 2.6, the coefficients l_1, l_2, l_4, l_8 are equal to zero, meaning that for the hot hatch to be the preferred option the decision maker must not assign any importance to: time spent unloading high priority containers, time spent retrieving high priority containers and total unit costs for both priorities. Most significantly, the hot hatches are the preferred option as long as the probability of non-compliance for high priority containers is of some importance to the decision maker. In addition, as shown in Table 2.6, the combined weight of importance of the performance measures associated with low priority containers is much higher than the corresponding to high priority containers.

RESULTS CORRESPONDING TO PRIORITY AT STORAGE YARD

Table 2.7 summarizes the results corresponding to priority at the storage yard for the different test cases.

Table 2.7: Region of optimality for priority at the storage yard								
	Case A: 25% HPC, 1000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
Solution:	Time at unloading	Time at retrieval	Non compl.	Total cost	Time at unloading	Time at retrieval	Non compl.	Total cost
λ*1	0.000	0.000	0.000	0.000	0.469	0.531	0.000	0.000
λ*2	-	-	-	-	-	-	-	-
λ*3	0.000	0.000	0.000	0.076	0.506	0.000	0.418	0.000
λ*4	0.000	0.154	0.000	0.000	0.488	0.000	0.358	0.000
λ*5	0.000	0.332	0.000	0.000	0.668	0.000	0.000	0.000
λ01–5	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000

	Case B: 50% HPC, 1000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
Solution:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
λ*1	0.000	0.000	0.000	0.000	0.458	0.542	0.000	0.000
λ*2	-	-	-	-	-	-	-	-
λ*3	0.000	0.000	0.000	0.000	0.000	0.077	0.923	0.000
λ*4	0.000	0.044	0.350	0.000	0.607	0.000	0.000	0.000
λ*5	0.000	0.044	0.350	0.000	0.607	0.000	0.000	0.000
λ01−5	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
λ01−7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000
λ01−8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000

	Case C: 25% HPC, 2000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
Solution:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
λ*1	0.000	0.000	0.000	0.000	0.000	0.542	0.458	0.000
λ*2	-	-	-	-	-	-	-	-
λ*3	0.000	0.000	0.000	0.125	0.000	0.623	0.252	0.000
λ*4	0.000	0.293	0.115	0.000	0.000	0.000	0.592	0.000
λ*5	0.000	0.603	0.000	0.000	0.000	0.000	0.397	0.000
λ01−5	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
λ01−7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000

	Case D: 50% HPC, 2000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
Solution:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
λ*1	0.000	0.000	0.227	0.000	0.000	0.510	0.263	0.000
λ*2	-	-	-	-	-	-	-	-
λ*3	0.000	0.000	0.000	0.000	0.000	0.136	0.183	0.681
λ*4	0.000	0.237	0.334	0.000	0.000	0.000	0.429	0.000
λ*5	0.000	0.237	0.334	0.000	0.000	0.000	0.429	0.000
λ01−5	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
λ01−7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000

As can be seen, priority at the storage yard is the preferred option for a wide combination of weights. The region of optimality for this system only has two decision criteria with zero coefficient, i.e., total time at unloading for high priority containers and total unit cost for low priority containers. The rest of the coefficients have, in general, values significantly different from zero.

As shown in Table 2.7, priority at the storage yard is the preferred option for a range of weights that include the case in which probability of non-compliance for high priority containers and total time at retrieval have a weak, though not negligible, importance.

RESULTS CORRESPONDING TO PRIORITY AT THE GATES

As in the previous sections, the proposed approach was applied to the system termed "priority at the gates." Table 2.8 summarizes the results corresponding to priority at the storage yard for the different test cases.

Table 2.8: Region of optimality for priority at the gates

	Case A: 25% HPC, 1000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
Solution:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
λ*1	0.000	0.000	0.000	0.000	0.414	0.501	0.085	0.000
λ*2	0.000	0.000	0.042	0.000	0.000	0.458	0.499	0.000
λ*3	0.000	0.000	0.000	0.076	0.506	0.000	0.418	0.000
λ*4	0.000	0.000	0.000	0.143	0.000	0.000	0.857	0.000
λ*5	0.000	0.000	0.000	0.151	0.000	0.060	0.789	0.000
λ01–7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000

	Case B: 50% HPC, 1000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
Solution:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
λ*1	0.000	0.000	0.000	0.000	0.296	0.487	0.216	0.000
λ*2	-	-	-	-	-	-	-	-
λ*3	0.000	0.000	0.000	0.000	0.000	0.077	0.923	0.000
λ*4	-	-	-	-	-	-	-	-
λ*5	0.000	0.000	0.000	0.033	0.000	0.171	0.796	0.000

	Case C: 25% HPC, 2000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
Solution:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
λ*1	0.000	0.000	0.000	0.017	0.000	0.588	0.395	0.000
λ*2	-	-	-	-	-	-	-	-
λ*3	0.000	0.000	0.000	0.125	0.000	0.623	0.252	0.000
λ*4	0.000	0.000	0.025	0.091	0.000	0.614	0.271	0.000
λ*5	0.000	0.000	0.000	0.125	0.000	0.623	0.252	0.000
λ01–6	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000

	Case D: 50% HPC, 2000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
Solution:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
λ*1	0.000	0.000	0.025	0.000	0.000	0.419	0.556	0.000
λ*2	-	-	-	-	-	-	-	-
λ*3	0.000	0.000	0.000	0.183	0.000	0.495	0.323	0.000
λ*4	0.000	0.000	0.016	0.108	0.000	0.694	0.093	0.000
λ*5	0.000	0.000	0.000	0.183	0.000	0.495	0.323	0.000

As can be seen, the region of optimality for priority at the gates exhibit three decision criteria with zero coefficient, i.e., total time at unloading for high priority containers, total time at retrieval for high priority containers and total unit cost for low priority containers.

As Table 2.8 shows, the region of optimality for this system is characterized for having negligible weights in three out of four performance measures associated to high priority containers, while the remaining one i.e., total unit cost, is of weak importance.

In summary, priority at the gates is the preferred option as long as:

- probability of non-compliance and total unit cost for high priority containers are of weak importance for the decision maker,
- total time at unloading, total time at retrieval and probability of non-compliance for low priority containers are of essential importance to the decision maker,
- total time at unloading for high priority containers, total time at retrieval for high priority containers and total unit cost for low priority containers are of no importance.

RESULTS CORRESPONDING TO PRIORITY SYSTEM IV (PS-IV)

Priority system IV (PS-IV) is the system that combines hot hatches with priority at the storage yard. As before, the corresponding range of optimality was determined. Table 2.9 summarizes the corresponding results.

Table 2.9: Region of optimality for priority system IV (PS-IV)

	Case A: 25% HPC, 1000 containers/week							
	$\lambda 1$	$\lambda 2$	$\lambda 3$	$\lambda 4$	$\lambda 5$	$\lambda 6$	$\lambda 7$	$\lambda 8$
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
Solution:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
$\lambda*1$	-	-	-	-	-	-	-	-
$\lambda*2$	0.000	0.000	0.275	0.000	0.000	0.621	0.105	0.000
$\lambda*3$	0.000	0.154	0.000	0.000	0.488	0.000	0.358	0.000
$\lambda*4$	0.000	0.000	0.000	0.143	0.000	0.000	0.857	0.000
$\lambda*5$	0.000	0.123	0.877	0.000	0.000	0.000	0.000	0.000
$\lambda01-1$	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$\lambda01-3$	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
$\lambda01-8$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000

	Case B: 50% HPC, 1000 containers/week							
	$\lambda 1$	$\lambda 2$	$\lambda 3$	$\lambda 4$	$\lambda 5$	$\lambda 6$	$\lambda 7$	$\lambda 8$
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
Solution:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
$\lambda*1$	0.000	0.000	0.093	0.000	0.120	0.787	0.000	0.000
$\lambda*2$	-	-	-	-	-	-	-	-
$\lambda*3$	0.000	0.044	0.350	0.000	0.607	0.000	0.000	0.000
$\lambda*4$	-	-	-	-	-	-	-	-
$\lambda*5$	0.000	0.111	0.889	0.000	0.000	0.000	0.000	0.000
$\lambda01-1$	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$\lambda01-3$	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000

	Case C: 25% HPC, 2000 containers/week							
	$\lambda 1$	$\lambda 2$	$\lambda 3$	$\lambda 4$	$\lambda 5$	$\lambda 6$	$\lambda 7$	$\lambda 8$
	Time at	Time at	Non	Total	Time at	Time at	Non	Total
Solution:	unloading	retrieval	compl.	cost	unloading	retrieval	compl.	cost
$\lambda*1$	0.000	0.000	0.038	0.000	0.000	0.554	0.408	0.000
$\lambda*2$	-	-	-	-	-	-	-	-
$\lambda*3$	0.000	0.293	0.115	0.000	0.000	0.000	0.592	0.000
$\lambda*4$	0.000	0.000	0.025	0.091	0.000	0.614	0.271	0.000
$\lambda*5$	0.000	0.000	0.782	0.000	0.000	0.000	0.218	0.000
$\lambda01-8$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000

	Case D: 50% HPC, 2000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
Solution:	Time at unloading	Time at retrieval	Non compl.	Total cost	Time at unloading	Time at retrieval	Non compl.	Total cost
λ*1	0.000	0.000	0.227	0.000	0.000	0.510	0.263	0.000
λ*2	-	-	-	-	-	-	-	-
λ*3	0.000	0.236	0.334	0.000	0.000	0.000	0.429	0.000
λ*4	0.000	0.000	0.106	0.108	0.000	0.694	0.093	0.000
λ*5	0.000	0.394	0.606	0.000	0.000	0.000	0.000	0.000
λ01−1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
λ01−3	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
λ01−8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000

As Table 2.9 shows, the combined weight of the decision criteria associated with high priority containers is comparable to the combined weights of the criteria corresponding to low priority containers. Both sets of coefficients have, in general, the same order of magnitude.

In summary, PS-IV is the preferred option as long as:

- probability of non-compliance for both priorities are of very strong importance to the decision maker,
- total time at retrieval and total unit cost for high priority containers are of weak importance to the decision maker,
- total time at unloading and total time at retrieval for low priority containers are of very strong importance to the decision maker.

RESULTS CORRESPONDING TO PRIORITY SYSTEM V (PS-V)

The range of optimality corresponding to priority system V (PS-V) is summarized in Table 2.10.

Table 2.10: Region of optimality for priority system V (PS-V)

	Case A: 25% HPC, 1000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
Solution:	Time at unloading	Time at retrieval	Non compl.	Total cost	Time at unloading	Time at retrieval	Non compl.	Total cost
λ*1	0.000	0.000	0.048	0.000	0.298	0.654	0.000	0.000
λ*2	0.000	0.000	0.286	0.000	0.000	0.714	0.000	0.000
λ*3	0.000	0.332	0.000	0.000	0.668	0.000	0.000	0.000
λ*4	0.000	0.000	0.000	0.151	0.000	0.060	0.789	0.000
λ*5	0.000	0.123	0.877	0.000	0.000	0.000	0.000	0.000
λ01−2	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
λ01−4	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000

	Case B: 50% HPC, 1000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
Solution:	Time at unloading	Time at retrieval	Non compl.	Total cost	Time at unloading	Time at retrieval	Non compl.	Total cost
λ*1	0.000	0.003	0.091	0.000	0.116	0.790	0.000	0.000
λ*2	-	-	-	-	-	-	-	-
λ*3	0.000	0.044	0.350	0.000	0.607	0.000	0.000	0.000
λ*4	0.000	0.000	0.000	0.033	0.000	0.171	0.796	0.000
λ*5	0.000	0.111	0.889	0.000	0.000	0.000	0.000	0.000
λ01–2	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
λ01–4	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000

	Case C: 25% HPC, 2000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
Solution:	Time at unloading	Time at retrieval	Non compl.	Total cost	Time at unloading	Time at retrieval	Non compl.	Total cost
λ*1	-	-	-	-	-	-	-	-
λ*2	-	-	-	-	-	-	-	-
λ*3	0.000	0.603	0.000	0.000	0.000	0.000	0.397	0.000
λ*4	0.000	0.000	0.000	0.125	0.000	0.623	0.252	0.000
λ*5	0.000	0.000	0.782	0.000	0.000	0.000	0.218	0.000
λ01–1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
λ01–2	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
λ01–3	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
λ01–4	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000

	Case D: 50% HPC, 2000 containers/week							
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
Solution:	Time at unloading	Time at retrieval	Non compl.	Total cost	Time at unloading	Time at retrieval	Non compl.	Total cost
λ*1	0.000	0.067	0.107	0.000	0.000	0.739	0.087	0.000
λ*2	-	-	-	-	-	-	-	-
λ*3	0.000	0.236	0.334	0.000	0.000	0.000	0.429	0.000
λ*4	0.000	0.000	0.000	0.183	0.000	0.495	0.323	0.000
λ*5	0.000	0.394	0.606	0.000	0.000	0.000	0.000	0.000
λ01–2	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
λ01–4	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000

As shown in Table 2.10, the region of optimality of PS-V has one decision criterion with zero weight i.e., total unit cost for low priority containers. In addition, the weights of importance of the decision criteria associated to high priority containers are much higher than in the previous systems.

PS-V would be the preferred option as long as:

- probability of non-compliance for high priority containers is of absolute importance to the decision maker,

- total time at retrieval for high priority containers is of essential importance to the decision maker,
- total time at unloading, total time at retrieval for low priority containers are of very strong importance to the decision maker.

CONCLUSIONS

The following are the main findings of this chapter which are related to both the methodology used and the results of the analyses.

ON THE APPROACH USED

a) The proposed approach seems to facilitate the analysis of the relationship between the optimality of a given alternative and the behavioral characteristics of the decision making process.

b) Since the assumed choice function is a convex combination of decision criteria, the proposed framework is not be able to determine the range of applicability of alternatives lying on a duality gap. In such a case, an alternative approach, e.g., analyzing the marginal rates of substitution among the alternatives may be used, though they will not be able to provide the same kind of insights than the proposed approach.

ON THE RANGE OF APPLICABILITY OF THE DIFFERENT SYSTEMS

c) Each of the systems analyzed in this research has a range of optimality in terms of the corresponding weights of importance for each of the decision criteria. As discussed in Section 2.3, the range of optimality is expressed as the set of all possible convex combinations of the extreme point solutions to the linear programming problem represented by equations 13 to 15. This section focuses on a less formal discussion of the range of optimality. Table 2.11 indicates the range of values that the corresponding parameter has taken in the different test cases. The notation for intensity of importance from Table 2.4 has been used to denote the range of values. The reader must not confuse the results presented in Table 2.11 with the range of optimality.

In general terms, if the combined weight of the decision criteria associated with high priority containers is assumed to be an indication of the importance given by the decision maker to the level of service for this type of container, a ranking order can be established among the different systems. The resulting ranking order and the summary of results is shown in Table 2.11.

Table 2.11: Summary of results								
	Priority 1				Priority 2			
	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
Operational system	Time at unloading	Time at retrieval	Non compl.	Total cost	Time at unloading	Time at retrieval	Non compl.	Total cost
Base case	0	0	0/+	0	0/++	++/++++	0/++	0
PS-III	0	0	0	0/+	0/++	0/++++	+/++++	0
PS-I	0	0	+	0	+	++/+++	0/++	0
PS-II	0	0/+++	0/++	0/+	0/++++	0/++	0/++++	0/++++
PS-IV	0/++++	0/++	0/++++	0/+	0/+++	0/+++	0/++++	0/++++
PS-V	0/++++	0/++++	0/++++	0/++++	0/+++	0/+++	0/+++	0

Where:
PS-I: Hot hatches
PS-II: Priority at storage yard, i.e., high priority containers stored on chassis
PS-III: Priority at the terminal gates, i.e., high priority containers receive preferential treatment at the terminal gates using AEI devices.
PS-IV: Combination of PS-I and PS-II
PS-V: Combination of PS-I, PS-II and PS-III

0: No importance
+: Weak importance
++: Essential importance
+++: Very strong importance
+++++: Absolute importance

As shown in Table 2.11, the base case would be the preferred alternative if the level of service corresponding to high priority containers is of no importance to the decision maker. If probability of non-compliance and total unit costs for high priority containers have a weak importance, them PS-III i.e., priority operations at the gates using AEI equipment, would be the preferred system. At the next level, PS-I, i.e., hot hatches are the preferred system as long as probability of non-compliance has a weak importance, though more important than in the previous case. PS-II, i.e., the system that involves storing high priority containers on chassis, is the preferred option for a wide combination of the parameters of total time at retrieval, probability of non-compliance and total unit cost for high priority containers. Finally, the systems that articulate service differentiation at various stages (i.e., PS-IV and PS-V) can be found. When the maximum importance is given to the level of service for high priority containers, PS-V is the preferred option.