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Scheduling and order selection in Liner Shipping

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Abstract

In this thesis we address the problem of scheduling a single ship operating on a liner shipping network. The scheduling process comprises two phases: (a) designating an initial time schedule considering pre-arranged contract orders, and a forecast of spot orders, and (b) defining the detailed schedule that maximizes profit, respecting the initial time schedule of part (a) and considering actual spot orders. We have proposed a novel model to formulate and solve the related scheduling problem; that is, a mixed integer linear program, suitably adapted for the business case of each phase. In this model profit maximization involves balancing: (a) the income collected from serving spot orders, and (b) the fuel consumption and CO_2 emissions by selecting the sailing speed and considering the ship's load. We have also performed an extensive computational study that analyzes the scheduling problem under various realistic shipping conditions. The results illustrate that the proposed method is suitable for scheduling practical liner shipping problems. The results also provide insights in effective scheduling of liner shipping under various conditions.

Εκτενής περίληψη

Εισαγωγή

Ο ρόλος της εμπορευματικής ναυτιλίας στο παγκόσμιο εμπόριο είναι πιθανότατα ο σημαντικότερος, κάτι που αποδεικνύεται από το γεγονός ότι το 2012 μεταφέρθηκαν 155 εκ. εμπορευματοκιβώτια (UNCTAD, 2013). Όσον αφορά την επίδραση της ναυτιλίας στο περιβάλλον, η Ευρωπαϊκή Επιτροπή πρότεινε οι εκπομπές που οφείλονται σε αυτόν τον τομέα, να μειωθούν 40% και αν είναι δυνατόν έως και 50% μέχρι το 2050 (European Commission, 2014). Ένας από τους τρόπους μείωσης των εκπομπών είναι και η μείωση της ταχύτητας. Ωστόσο όχι με τρόπο επιζήμιο προς την εταιρεία, αλλά ικανό να διατηρήσει την ποιότητα στις μεταφορές χωρίς να υπάρξουν οικονομικές απώλειες.

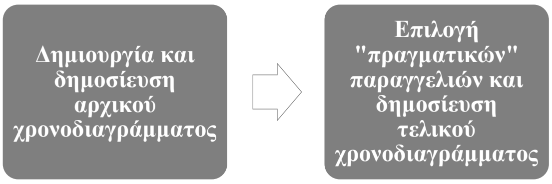
Η εμπορευματική ναυτιλία χωρίζεται σε 3 βασικούς τομείς (Lawrence, 1972): α) μεταφορά φορτίων σε τακτική γραμμή/ καθορισμένο δρομολόγιο, β) μεταφορά φορτίων σε μη καθορισμένο δρομολόγιο, γ) βιομηχανική μεταφορά. Στην παρούσα διπλωματική εργασία θα ασχοληθούμε με τον τομέα της μεταφοράς εμπορευματοκιβωτίων μέσω θαλάσσης σε τακτική γραμμή και θα εστιάσουμε στην μείωση της ταχύτητας, λαμβάνοντας όμως υπ’ όψιν το επιχειρηματικό περιβάλλον με ρεαλιστικό τρόπο.

Όπως απεικονίζεται στο Σχήμα 1, το επιχειρηματικό μοντέλο τακτικής εμπορευματικής μεταφοράς αποτελείται από μία σειρά διαδικασιών, με πρώτη αυτή της σχεδίασης του δικτύου. Η σχεδίαση του δικτύου βασίζεται σε α) μεθόδους πρόβλεψης των παραγγελιών και β) προϋπογεγραμμένα συμβόλαια. Στη συνέχεια το δίκτυο δημοσιεύεται, με σκοπό την προσέλκυση "πραγματικών" παραγγελιών. Έπειτα, γίνεται διαχείριση στόλου, με την εταιρεία να τοποθετεί τα πλοία σε συγκεκριμένα δρομολόγια και να αναθέτει σε κάθε πλοίο τις "πραγματικές" παραγγελίες που πρέπει να εξυπηρετήσει. Τέλος, ανακοινώνεται το χρονοδιάγραμμα του κάθε πλοίου.

Σχήμα 1 Επιχειρηματικό μοντέλο της θαλάσσιας εμπορευματικής τακτικής μεταφοράς

Ορισμός προβλήματος

Λαμβάνοντας υπ’ όψιν το παραπάνω επιχειρηματικό μοντέλο των θαλάσσιων τακτικών εμπορευματικών μεταφορών, στην παρούσα διπλωματική εργασία θεωρήσαμε δεδομένο το δίκτυο πλεύσης και μελετήσαμε την περίπτωση ενός μεμονωμένου πλοίου τακτικών γραμμών. Συνεπώς, το προαναφερθέν επιχειρηματικό μοντέλο αντιμετωπίστηκε σε δύο σκέλη όπως παρουσιάζεται στο παρακάτω Σχήμα 2.



Σχήμα 2 Προσέγγιση επιχειρηματικού μοντέλου της θαλάσσιας εμπορευματικής τακτικής μεταφοράς

Αναλυτικότερα, στο πρώτο σκέλος, θεωρούμε δεδομένο το δίκτυο πλεύσης, δηλαδή την σειρά επίσκεψης των λιμανιών, καθώς και την ενωρίτερη στιγμή αναχώρησης από το πρώτο λιμάνι και την ύστατη στιγμή άφιξης στο τελευταίο. Επίσης, θεωρούμε δεδομένα τα αποτελέσματα της πρόβλεψης ζήτησης των παραγγελιών, καθώς και την πραγματική ζήτηση των προϋπογεγραμμένων συμβολαίων. Υποθέτοντας, λοιπόν, τις προβλεπόμενες παραγγελίες και λαμβάνοντας υπ’ όψιν τα πραγματικά προϋπογεγραμμένα συμβόλαια, το μαθηματικό μοντέλο αποδίδει ένα αρχικό χρονοδιάγραμμα, το οποίο και δημοσιεύεται, με σκοπό την προσέλκυση "πραγματικών" παραγγελιών.

Όσον αφορά το δεύτερο σκέλος του μοντέλου, σεβόμενοι το αρχικό χρονοδιάγραμμα αποδίδουμε το τελικό δρομολόγιο, με στόχο τη μεγιστοποίηση του κέρδους της εμπορευματικής μεταφοράς, που είναι αποτέλεσμα α) των εσόδων που προκύπτουν από τα προϋπογεγραμμένα συμβόλαια και τις "πραγματικές" παραγγελίες και β) των εξόδων πλεύσης. Αναφορικά με τα έσοδα, θεωρούμε ότι τα συμβόλαια που έχουν χρησιμοποιηθεί στο πρώτο σκέλος εξακολουθούν να πρέπει να εξυπηρετηθούν και αντικαθιστούμε τις προβλεπόμενες παραγγελίες με "πραγματικές" παραγγελίες. Αναλυτικότερα, το έσοδο, τόσο για τα συμβόλαια όσο και για τις παραγγελίες, λογίζεται ως το σύνολο των εμπορευματοκιβωτίων επί την απόσταση, την οποία διανύουν μέχρι το σημείο παράδοσης επί την τιμή χρέωσης ($) ανά μετρική μονάδα. Από την άλλη, τα έξοδα πλεύσης είναι απόρροια της κατανάλωσης καυσίμου, το οποίο προκύπτει από την ταχύτητα και τον παράγοντα φόρτωσης του πλοίου (Corbett *et al.*, 2009b; Kontovas and Psaraftis, 2011).

Μαθηματική μοντελοποίηση του προβλήματος

Σε αυτή την ενότητα παρουσιάζεται αναλυτικά ο τρόπος προσέγγισης και επίλυσης του επιχειρηματικού μοντέλου που περιγράφηκε στην προηγούμενη ενότητα με την χρήση ενός μαθηματικού μοντέλου μικτού ακέραιου προγραμματισμού. Στη συνέχεια, παρατίθενται οι συμβολισμοί που χρησιμοποιούνται για το μαθηματικό μας μοντέλο.

Θεωρούμε:

N	Σύνολο λιμανιών
K	Σύνολο διακριτών τιμών k ταχύτητας πλεύσης
L	Σύνολο διακριτών τιμών l του επιπέδου φόρτωσης
Q	Συνολική χωρητικότητα πλοίου
q_i	Ποσότητα φορτίου κατά την αναχώρηση του πλοίου από το λιμάνι, $i = 1, \ldots, N-1$
p_i	Ποσότητα παραλαβής συμβολαίων στο λιμάνι i
d_i	Ποσότητα παράδοσης συμβολαίων στο λιμάνι i
W_i	Συνολικό έσοδο συμβολαίων στο λιμάνι i
O	Σύνολο παραγγελιών
π_i^j	Ποσότητα παραλαβής παραγγελίας $j, j \in O$ στο λιμάνι i
δ_i^j	Ποσότητα παράδοσης παραγγελίας $j, j \in O$ στο λιμάνι i
r_j	Δυαδική μεταβλητή επιλογής ή μη παραγγελίας $j, j \in O$
Φ_j	Έσοδο παραγγελίας $j, j \in O$
s_i	Χρονική στιγμή εκκίνησης της εξυπηρέτησης στο λιμάνι $i, i \in N$
t_{ikl}	Χρόνος πλεύσης στο λιμάνι i με ταχύτητα $k \in K$ και επίπεδο φόρτωσης $l \in L$
C_{ikl}	Κόστος πλεύσης στο λιμάνι i σε με ταχύτητα $k \in K$ κι επίπεδο φόρτωσης $l \in L$
x_{ikl}	Δυαδική μεταβλητή αναχώρησης από το λιμάνι i με ταχύτητα $k \in K$ και επίπεδο φόρτωσης $l \in L$
c	Ρυθμός φορτοεκφόρτωσης σε κάθε λιμάνι i, με μονάδα μέτρησης εμπορευματοκιβώτια/ημέρα
a, b	Αρχική και τελική ημερομηνία εκκίνησης και ολοκλήρωσης του ταξιδιού
y_l	Κάτω όριο επιπέδου φορτίου l, με μονάδα μέτρησης % φορτίο
u_l	Άνω όριο επιπέδου φορτίου l, με μονάδα μέτρησης % φορτίο
BM	Πολύ μεγάλος αριθμός, $BM >> 1$

Με αφορμή την ιδέα του (Fagerholt *et al.*, 2010), ο οποίος μετάτρεψε ένα μη γραμμικό μοντέλο σε γραμμικό (χρησιμοποιώντας διακριτοποίηση στις χρονικές αφίξεις) προτείνουμε μία εναλλακτική μέθοδο, η οποία χρησιμοποιεί ένα διακριτό αριθμό ταχυτήτων πλεύσης και διακριτά επίπεδα παράγοντα φόρτωσης. Για να μοντελοποιήσουμε το πρόβλημα μας θεωρούμε α) N το σύνολο των λιμανιών επίσκεψης, β) K το σύνολο διακριτών τιμών k ταχύτητας πλεύσης, από τις οποίες μπορεί να επιλέξει το πλοίο μεταξύ των λιμανιών επίσκεψης, και γ) L το σύνολο των διακριτών επιπέδων φορτίου l, με τα οποία μπορεί να ταξιδέψει το πλοίο μεταξύ των λιμανιών επίσκεψης. Το επίπεδο κάθε παράγοντα φορτίου καθορίζεται από ένα εύρος τιμών (y_l, u_l), όπου y_l είναι το κάτω όριο και u_l το άνω όριο που αφορά τον παράγοντα φορτίου l.

Σύμφωνα με την παραπάνω προτεινόμενη μέθοδο, θεωρούμε ένα γράφο $G(E, A)$ με κόμβους $E = \{1, \dots, N\}$, που αντιπροσωπεύουν τα λιμάνια του τακτικού δρομολογίου N, και με ακμές $A = \{(i, i+1) | i = 1, \dots, N-1\}$.

Αναλυτικότερα, θεωρούμε ότι η εμπορευματική μεταφορά ξεκινά έπειτα από την προκαθορισμένη ενωρίτερη στιγμή αναχώρησης από το πρώτο λιμάνι και ολοκληρώνεται πριν από την προκαθορισμένη ύστατη στιγμή άφιξης στο τελευταίο λιμάνι.

Θεωρούμε ότι Q είναι η συνολική χωρητικότητα του πλοίου και q_i η ποσότητα κάλυψης της χωρητικότητας όταν το πλοίο αναχωρεί από κάθε λιμάνι. Η χωρητικότητα του πλοίου καλείται να καλυφθεί από προϋπογεγραμμένα συμβόλαια και παραγγελίες. Από τα προϋπογεγραμμένα συμβόλαια, θεωρούμε p_i και d_i ότι είναι οι ποσότητες παραλαβής και παράδοσης συμβολαίων σε κάθε λιμάνι i, καθώς και W_i το έσοδο που προκύπτει από την εξυπηρέτηση τους. Να σημειώσουμε ότι d_1 και p_N, όπου είναι η παράδοση συμβολαίων στο λιμάνι 1 και η παραλαβή συμβολαίων στο λιμάνι N, είναι μηδενικές ποσότητες. Όσον αφορά τις παραγγελίες, ορίζουμε O το σύνολο των παραγγελιών και θεωρούμε π_i^j και δ_i^j τις ποσότητες εμπορευματοκιβωτίων της παραγγελίας $j \in O$, που είναι προς παραλαβή και παράδοση στο λιμάνι i. Επίσης, ορίζουμε ως r_j δυαδική μεταβλητή, η οποία παίρνει την τιμή 1 αν η παραγγελία $j \in O$ εξυπηρετείται και 0 σε κάθε άλλη περίπτωση. Ως Φ_j ορίζουμε το έσοδο από την εξυπηρέτηση της παραγγελίας $j \in O$.

Θεωρούμε ως s_i τη χρονική στιγμή έναρξης της εμπορευματικής μεταφοράς στο λιμάνι i. Επίσης, θεωρούμε t_{ikl} το χρόνο πλεύσης στο λιμάνι i με επιλεγμένη ταχύτητα $k \in K$ και επίπεδο φόρτωσης $l \in L$. Λαμβάνουμε υπ' όψιν και την παράμετρο c που αποτελεί το χρόνο φορτοεκφόρτωσης ενός εμπορευματοκιβωτίου σε κάθε λιμάνι.

Η δυαδική μεταβλητή $x_{ikl}, i = 1, \dots, N-1$ λαμβάνει την τιμή 1 όταν το πλοίο αναχωρεί από το λιμάνι i με ταχύτητα $k \in K$ και επίπεδο φόρτωσης $l \in L$ και 0 σε κάθε άλλη περίπτωση.

Επίσης, θεωρούμε C_{ikl} το κόστος πλεύσης στο λιμάνι $i = 1, \dots, N-1$ με ταχύτητα $k \in K$ και επίπεδο φόρτωσης $l \in L$. Τέλος, το κόστος πλεύσης εξαρτάται από την απόσταση μεταξύ διαδοχικών λιμανιών, από την ταχύτητα πλεύσης k, το επίπεδο φόρτωσης l.

Μαθηματική μοντελοποίηση- Πρώτο σκέλος

Η αντικειμενική συνάρτηση μεγιστοποίησης του κέρδους της εμπορευματικής μεταφοράς αποτελείται από τα εξής τρία μέλη: α) το έσοδο παραγγελιών, β) το έσοδο προϋπογεγραμμένων συμβολαίων και γ) το έξοδο εμπορευματικής μεταφοράς. Αναλυτικότερα, το πρώτο μέλος αφορά το έσοδο που προκύπτει από την εξυπηρέτηση των προβλεπόμενων παραγγελιών, με την μεταβλητή απόφασης r_j να εξασφαλίζει ότι μόνο το έσοδο από τις εξυπηρετούμενες παραγγελίες υπολογίζεται στο έσοδο των παραγγελιών. Το δεύτερο μέλος αφορά το έσοδο των προϋπογεγραμμένων συμβολαίων που εξυπηρετούνται στο λιμάνι i. Τέλος, το τρίτο μέλος καθορίζει το συνολικό κόστος πλεύσης, με βάση την ταχύτητα πλεύσης και το επίπεδο φόρτωσης στα λιμάνια του δεδομένου δικτύου τακτικής εμπορευματικής μεταφοράς με μεταβλητή απόφασης x_{ikl}.

$$max\, P = \sum_{j \in O} \Phi_j r_j + \sum_{i \in N} W_i - \sum_{l \in L} \sum_{k \in K} \sum_{i=1}^{N-1} C_{ikl} x_{ikl} \tag{1}$$

Στην συνέχεια περιγράφονται οι περιορισμοί του προβλήματος. Ο περιορισμός (2) διασφαλίζει ότι από κάθε ένα λιμάνι το πλοίο θα αναχωρεί με μία ταχύτητα και ένα επίπεδο φόρτωσης. Ο περιορισμός (3) διασφαλίζει ότι η ποσότητα φόρτωσης κατά την αναχώρηση του πλοίου από κάθε λιμάνι δεν θα ξεπερνάει τη συνολική χωρητικότητα του. Ο περιορισμός (4) καθορίζει την ποσότητα φόρτωσης κατά την αναχώρηση του πλοίου από κάθε λιμάνι, που προέρχεται τόσο από τις προβλεπόμενες παραγγελιές όσο και από τα προϋπογεγραμμένα συμβόλαια. Ο περιορισμός (5) καθορίζει το επιλεγμένο επίπεδο φόρτωσης κατά την αναχώρηση του πλοίου από κάθε λιμάνι. Ο περιορισμός μας διασφαλίζει το επίπεδο φορτίου να υπολογίζεται μόνο από τις επιλεγόμενες παραγγελίες και γι’ αυτό το λόγο χρησιμοποιούμε ένα μεγάλο αριθμό BM. Ο περιορισμός (6) ορίζει τη χρονική στιγμή εκκίνησης της εξυπηρέτησης στο λιμάνι i. Οι περιορισμοί (7) και (8) διασφαλίζουν ότι η εκκίνηση της εμπορευματικής μεταφοράς θα πραγματοποιηθεί μετά την προκαθορισμένη στιγμή έναρξης και θα ολοκληρωθεί πριν την προκαθορισμένη στιγμή λήξης της εμπορευματικής μεταφοράς. Τέλος, οι περιορισμοί (9) έως (11) καθορίζουν το επιτρεπόμενο εύρος τιμών για τις μεταβλητές απόφασης.

$$\sum_{l\in L}\sum_{k\in K} x_{ikl} = 1, \quad i = 1,\dots,N-1 \tag{2}$$

$$0 \leq q_i \leq Q, \quad i = 1,\dots,N \tag{3}$$

$$q_{i+1} - \sum_{j\in O}\left(\pi_{i+1}^{j} - \delta_{i+1}^{j}\right) r_j - \left(p_{i+1} - d_{i+1}\right) = q_i, \quad i = 1,\dots,N-1 \tag{4}$$

$$BM\left(1 - \sum_{k\in K} x_{ikl}\right) + y_l \leq q_i \leq u_l - BM\left(1 - \sum_{k\in K} x_{ikl}\right), \quad i = 1,\dots,N, k\in K, l\in L \tag{5}$$

$$s_i + \sum_{l\in L}\sum_{k\in K} t_{ikl}x_{ikl} + c\sum_{j\in O}\left(\pi_i^{j} + \delta_i^{j}\right) r_j + c\left(p_i + d_i\right) = s_{i+1}, \quad i = 1,\dots,N-1 \tag{6}$$

$$a \leq s_1, \tag{7}$$

$$s_N \leq b, \tag{8}$$

$$s_i \geq 0, \quad i = 2,\dots,N \tag{9}$$

$$r_j \in \{0,1\}, \quad j = 1,\dots,O \tag{10}$$

$$x_{ikl} \in \{0,1\}, \quad i = 1,\dots,N-1, k\in K, l\in L \tag{11}$$

Μαθηματική μοντελοποίηση – Δεύτερο σκέλος

Στο δεύτερο σκέλος του μαθηματικού μοντέλου, οι προβλεπόμενες παραγγελίες μετατρέπονται σε "πραγματικές" παραγγελίες. Χρησιμοποιούμε το χρονοδιάγραμμα που μας δίνει η επίλυση του πρώτου μοντέλου και επιλύουμε το σκέλος 2, βασιζόμενοι στον τρόπο επίλυσης που χρησιμοποιήσαμε στο πρώτο σκέλος του μοντέλου, αλλά εισάγοντας έναν νέο περιορισμό. Ο περιορισμός (12) αφορά χρονικά παράθυρα, τα οποία τοποθετούνται στις υπάρχουσες χρονικές στιγμές που μας δίνει το μοντέλο 1, με στόχο να δώσουμε με σαφήνεια το τελικό χρονοδιάγραμμα του πλοίου.

$$\mathrm{a_i} \leq \mathrm{s_i} \leq \mathrm{b_i}, \quad \mathrm{i} = 1,\dots,\mathrm{N} \tag{12}$$

Μέθοδος επίλυσης

Όλα τα μαθηματικά μοντέλα κωδικοποιήθηκαν σε περιβάλλον Mathwork’s Matlab 2014a σε συνδυασμό με το Gurobi optimizer 5.6.0 σε λογισμικό σύστημα Windows 32bit σε υπολογιστή με επεξεργαστή Intel i5 και 4GB μνήμη RAM.

Πειραματική διερεύνηση

Μία σειρά από πειράματα δημιουργήθηκε με σκοπό α) να εκτιμηθεί η σημασία της ομαλότητας του "προφίλ" των προϋπογεγραμμένων συμβολαίων, δηλαδή της χωρητικότητας που καταλαμβάνουν τα προϋπογεγραμμένα συμβόλαια στη συνολική χωρητικότητα του πλοίου, και β) να προσδιοριστεί το καταλληλότερο μέγεθος των παραγγελιών, καθώς και το καταλληλότερο μήκος της εμπορευματικής μεταφοράς των παραγγελιών, που επηρεάζουν τα οικονομικά δεδομένα και το τελικό χρονοδιάγραμμα του πλοίου. Συμπερασματικά, μελετούμε τα χαρακτηριστικά των δύο παραμέτρων του προβλήματος που επηρεάζουν τα χαρακτηριστικά της εμπορευματικής μεταφοράς, δηλαδή α) των προϋπογεγραμμένων συμβολαίων και β) των παραγγελιών.

Αναλυτικότερα, για την πειραματική διερεύνηση του προτεινόμενου μαθηματικού μοντέλου μελετήθηκε ένα πλοίο τακτικής γραμμής που επισκέπτεται δύο φορές ένα δίκτυο 15 λιμανιών. Στον παρακάτω Πίνακα 1 παρατίθενται οι κύριες παραδοχές που λήφθηκαν υπ’ όψιν κατά τη διεκπεραίωση της πειραματικής διερεύνησης.

Πίνακας 1 Κύριες παραδοχές πειραματικής διερεύνησης

Δίκτυο	Αριθμός λιμανιών ανά κύκλο εμπ. μεταφοράς	15
	Αριθμός κύκλων εμπ. μεταφοράς	2
	Ενδιάμεση απόσταση λιμανιών	1.500-2.500 Ναυτικά Μίλια
	Ρυθμός φορτοεκφόρτωσης	5.000 εμπορευματοκιβώτια / ημέρα
	Διάρκεια εμπ. μεταφοράς	210 ημέρες
	Χρονικό παράθυρο σε κάθε λιμάνι	2 ημέρες
Πλοίο	Επιλεγόμενο πλοίο	Emma Maersk
	Χωρητικότητα πλοίου	15.000 εμπορευματοκιβώτια
Οικονομικές αναλογίες	Αναλογία εσόδου	0,1$ ανά εμπορευματοκιβώτιο-Ναυτ. μίλι
	Τιμή καυσίμου	0,65$/ λίτρο
Ταχύτητα	Εύρος ταχύτητας	10-25 κόμβοι
	Επίπεδα ταχύτητας	16
Παράγοντας φόρτωσης	Εύρος παράγοντα φόρτωσης	0-100%

	Επίπεδα παράγοντα φόρτωσης	10
Ζήτηση	Ζήτηση παραγγελιών	217.500 εμπορευματοκιβώτια·λιμάνια/2 κύκλους εμπ. μεταφοράς
	"Προφίλ" συμβολαίων	50% (σ=0%, 2%, 4%, 8%, 16%)

Όπως προαναφέρθηκε, μελετούμε τα χαρακτηριστικά α) των προϋπογεγραμμένων συμβολαίων και β) των παραγγελιών που λαμβάνουν μέρος στην εμπορευματική μεταφορά.

Όσον αφορά, λοιπόν, τα προϋπογεγραμμένα συμβόλαια, υποθέτουμε ότι καταλαμβάνουν, κατά μέση τιμή, το 50% της χωρητικότητας του πλοίου. Στη συνέχεια, εξετάζουμε 5 διαφορετικές τυπικές αποκλίσεις: σ = 0%, 2%, 4%, 8%, 16% σε αυτή τη μέση τιμή. Με αυτόν τον τρόπο δημιουργούμε πέντε "προφίλ" των συμβολαίων, δηλαδή της χωρητικότητας που καταλαμβάνουν τα προϋπογεγραμμένα συμβόλαια στη συνολική χωρητικότητα του πλοίου, ξεκινώντας από το πιο ομαλό "προφίλ", με τυπική απόκλιση ίση με το μηδέν, έως το πιο ανώμαλο "προφίλ", με τυπική απόκλιση ίση με 16%, (CPSD-Contract Profile Standard Deviation). Σε κάθε περίπτωση, η εναπομένουσα χωρητικότητα καλείται να καλυφθεί από "πραγματικές" παραγγελίες.

Όσον αφορά τώρα τις παραγγελίες, μελετούμε τις εξής δύο παραμέτρους: α) το μέγεθος των παραγγελιών (V) και β) το μήκος της εμπορευματικής μεταφοράς των παραγγελιών (T), υποθέτοντας δύο επίπεδα, υψηλό (H) και χαμηλό (L) για κάθε μία από τις παραμέτρους όπως αυτές παρουσιάζονται και στον παρακάτω Πίνακα 2.

Πίνακας 2 Κατηγοριοποίηση παραμέτρων της πειραματικής διερεύνησης

Παράμετροι	**Επίπεδο**	**Περιγραφή**
Μέγεθος παραγγελιών (V), σε εμπορευματοκιβώτια	Υψηλό (H)	800 εμπορευματοκιβώτια, $\sigma = 200$
	Χαμηλό (L)	200 εμπορευματοκιβώτια, $\sigma = 50$
Μήκος εμπορευματικής μεταφοράς παραγγελιών (T), σε αριθμό λιμανιών	Υψηλό (H)	11 λιμάνια, $\sigma = 2$
	Χαμηλό (L)	2 λιμάνια, $\sigma = 1$

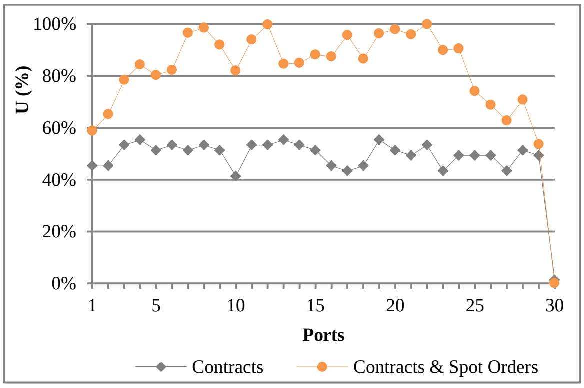
Συνεπώς, δημιουργούμε τέσσερα διαφορετικά σενάρια (V, T) σχετικά με τις παραγγελίες, τα οποία εφαρμόζονται στα πέντε διαφορετικά "προφίλ" προϋπογεγραμμένων συμβολαίων (CPSD). Συνολικά επιλύουμε είκοσι περιπτώσεις, τις οποίες επαναλαμβάνουμε εκατό φορές (2.000 περιπτώσεις).

i. (H, H) Σενάριο: V=High, T=High για 5 διαφορετικά "προφίλ" συμβολαίων
ii. (L, H) Σενάριο: V=Low, T=High για 5 διαφορετικά "προφίλ" συμβολαίων
iii. (L, L) Σενάριο: V=Low, T=Low για 5 διαφορετικά "προφίλ" συμβολαίων
iv. (H, L) Σενάριο: V=High, T=Low για 5 διαφορετικά "προφίλ" συμβολαίων

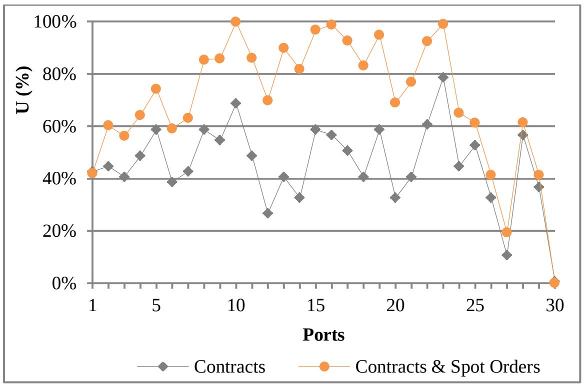
Αξιολόγηση της σημασίας του "προφίλ" των προϋπογεγραμμένων συμβολαίων

Στα παρακάτω Σχήματα 2α και 2β απεικονίζονται τα αποτελέσματα μίας περίπτωσης του σεναρίου (H, H) και αντίστοιχα στα Σχήματα 3α και 3β μίας περίπτωσης του σεναρίου (L, L) για δύο διαφορετικά "προφίλ" των προϋπογραμμένων συμβολαίων (CPSD-4%, CPSD-σ=16%), σε σχέση με την αξιοποίηση της συνολικής εκμετάλλευσης της χωρητικότητας και της ταχύτητας πλεύσης.

Η χωρητικότητα του πλοίου (Σχήμα 2α) αξιοποιείται καλύτερα στην περίπτωση του ομαλότερου "προφίλ" (CPSD-4%) και αυτό αποδεικνύεται και από την μέση τιμή της, η οποία είναι 84%, σε αντίθεση με τη μέση τιμή για CPSD-16% (Σχήμα 2β), που είναι 73% στην περίπτωση του σεναρίου (H, H).

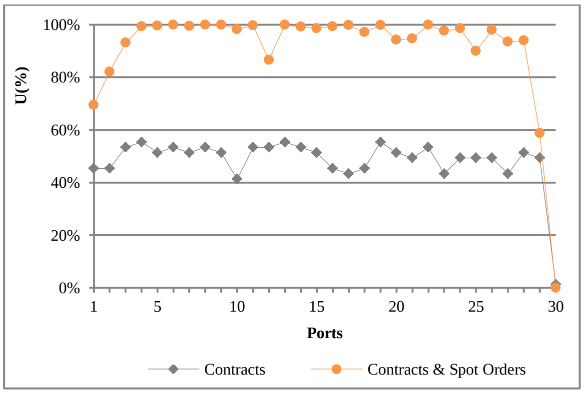


Σχήμα 2α Αξιοποίηση της χωρητικότητας του πλοίου για CPSD- % στο $(\boldsymbol{H}, \boldsymbol{H})$ σενάριο

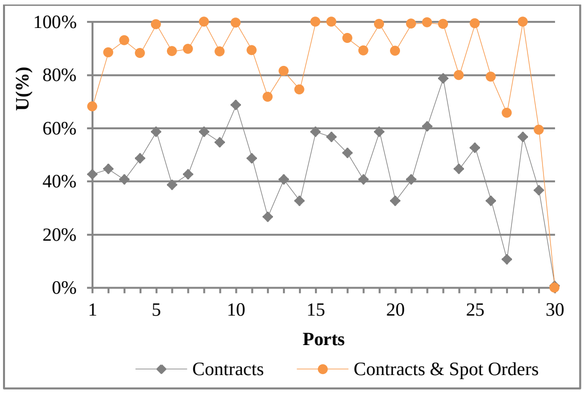


Σχήμα 2β Αξιοποίηση της χωρητικότητας του πλοίου για CPSD-16% στο $(\boldsymbol{H}, \boldsymbol{H})$ σενάριο

Αντίστοιχα είναι και τα αποτελέσματα του σεναρίου (L, L), όπου η μέση τιμή εκμετάλλευσης του ομαλότερου "προφίλ" (CPSD-4%) (Σχήμα 3α) είναι 94%, σε αντίθεση με τη μέση τιμή για CPSD-16% (Σχήμα 3β), που είναι 89%.



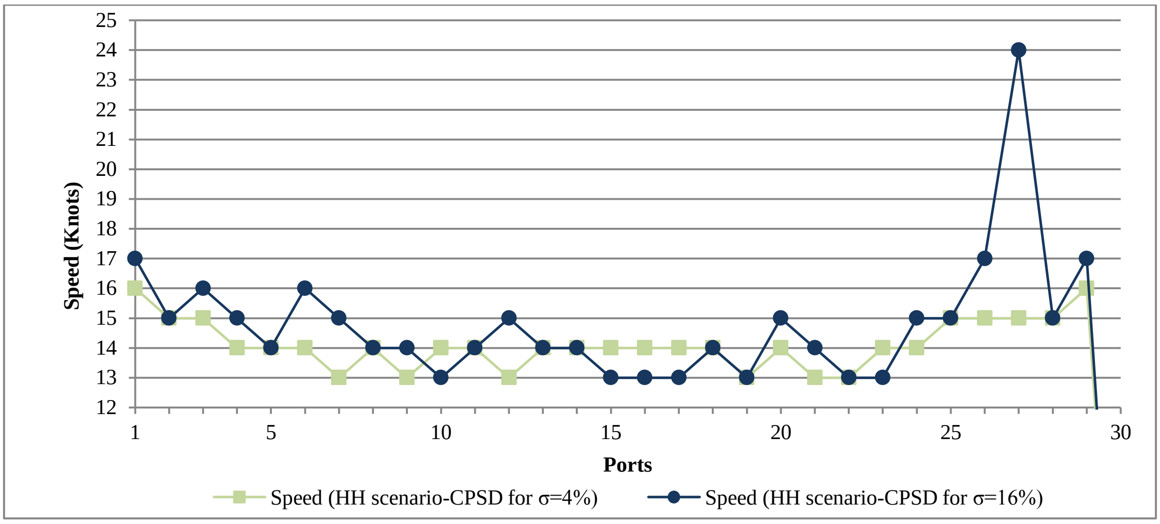
Σχήμα 3α Αξιοποίηση της χωρητικότητας του πλοίου για CPSD-4% στο $(\mathbf{L}, \mathbf{L})$ σενάριο



Σχήμα 3β Αξιοποίηση της χωρητικότητας του πλοίου για CPSD-16% στο $(\mathbf{L}, \mathbf{L})$ σενάριο

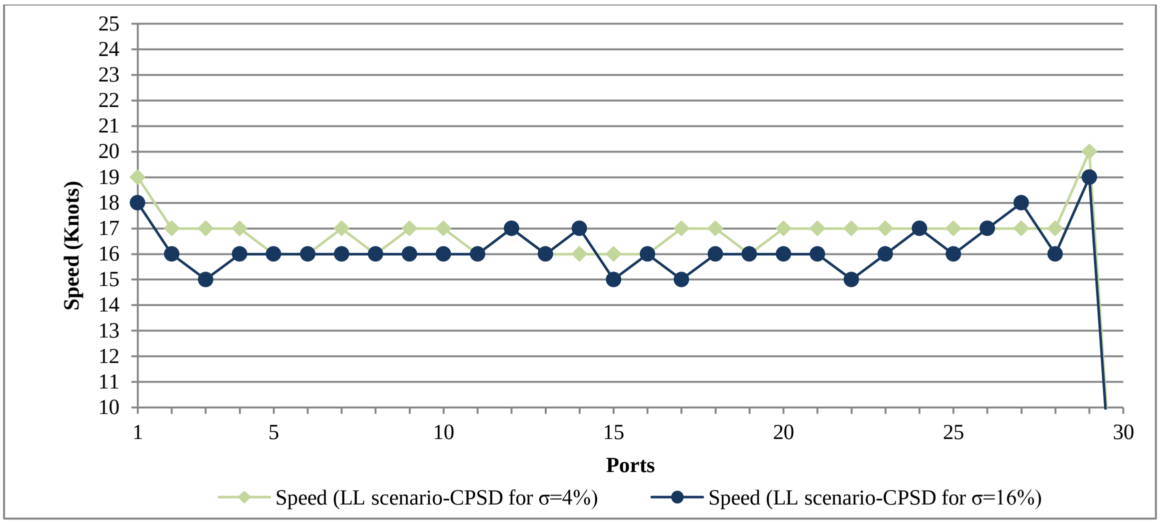
Συνεπώς, όσο πιο ομαλό είναι το "προφίλ" της χωρητικότητας που καταλαμβάνουν τα προϋπογεγραμμένα συμβόλαια, τόσο αυξάνονται και τα επίπεδα καλύτερης εκμετάλλευσης της συνολικής χωρητικότητας του πλοίου στην περίπτωση των σεναρίων (H, H) και (L, L).

Όσον αφορά την ταχύτητα πλεύσης στην περίπτωση του σεναρίου (H, H) (Σχήμα 4α), ακολουθεί την ομαλότητα του "προφίλ", που σημαίνει ότι όταν το "προφίλ" είναι ομαλό (CPSD-4%), η τυπική απόκλιση της ταχύτητα είναι μόλις 0,83knots, ενώ όσο πιο ανώμαλο το "προφίλ" των προϋπογεγραμμένων συμβολαίων" (CPSD-16%), η τυπική απόκλιση της ταχύτητας που καταγράφεται είναι 2,15knots.



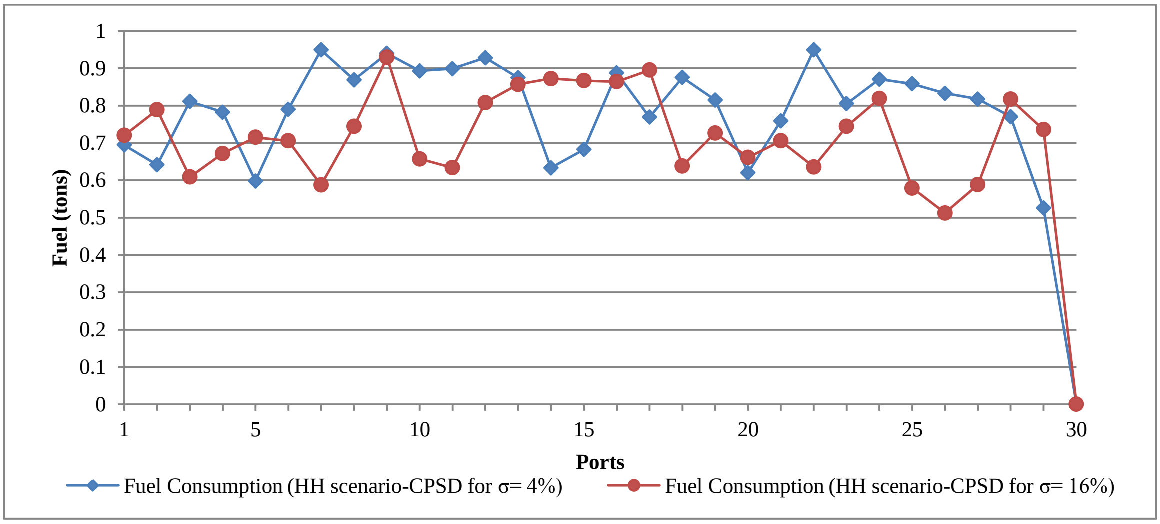
Σχήμα 4α Προφίλ ταχυτήτων για CPSD-4% και CPSD-16%, (H, H) σενάριο

Στα παρακάτω Σχήμα 4β, απεικονίζονται οι τιμές της ταχύτητας πλεύσης στην περίπτωση του σεναρίου (L, L), οι οποίες δεν μεταβάλλονται σε σχέση με το είδος του "προφίλ" των προϋπογεγραμμένων συμβολαίων. Αυτό που αξίζει να σημειωθεί είναι ότι οι τιμές των ταχυτήτων πλεύσης είναι μεγαλύτερες σε σχέση με την περίπτωση του προηγούμενου σεναρίου (H, H), γεγονός που σχετίζεται με τα χαρακτηριστικά της παραγγελίας που αναλύονται στην επόμενη ενότητα.



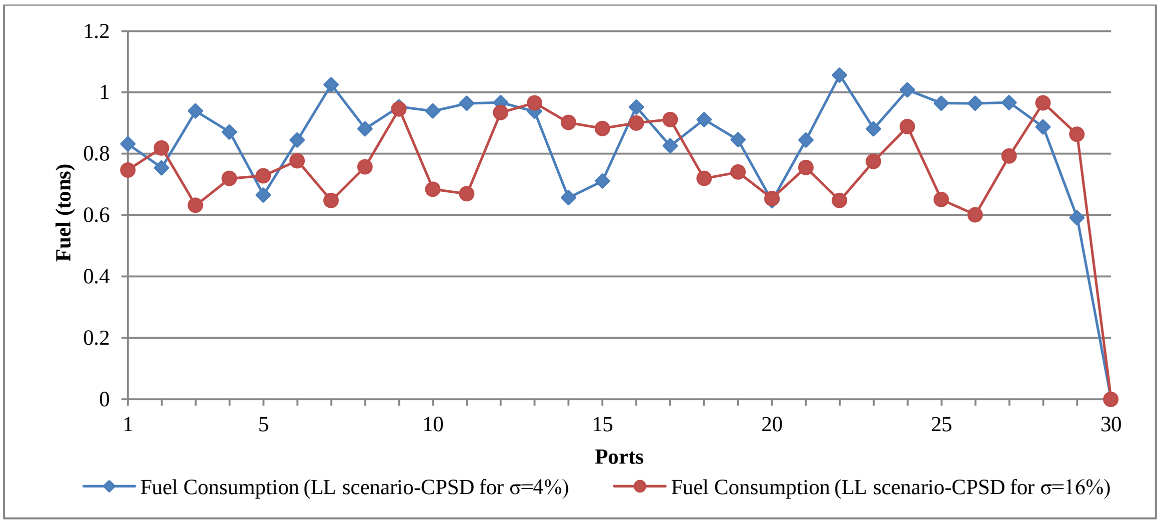
Σχήμα 4β Προφίλ ταχυτήτων για CPSD-4% και CPSD-16%, (L, L) σενάριο

Αναφορικά με την κατανάλωση καυσίμου του σεναρίου (H, H) για CPSD-16%, φαίνεται να είναι χαμηλότερη και πιο σταθερή σε σύγκριση με την κατανάλωση καυσίμου για CPSD-4% (Σχήμα 5α). Η μέση τιμή της κατανάλωσης καυσίμου για CPSD-16% είναι 0,72 τόνοι ανά διαδρομή με τυπική απόκλιση 0,10. Εν αντιθέσει, η μέση τιμή της κατανάλωσης καυσίμου για CPSD-4% είναι 0,8 τόνοι ανά διαδρομή και τυπική απόκλιση ίση με 0,11. Τα αποτελέσματα θεωρούνται αναμενόμενα καθώς τόσο η μέση τιμή της ταχύτητας όσο και η μέση τιμή του φορτίου είναι υψηλότερες για CPSD-4%.



Σχήμα 5α Προφίλ κατανάλωσης καυσίμου για CPSD-4% και CPSD-16%, (H, H) σενάριο

Αναφορικά με το σενάριο (L, L) Σχήμα 5β, η κατανάλωση καυσίμου για CPSD-16% δείχνει να είναι χαμηλότερη σε σύγκριση με την κατανάλωση καυσίμου για CPSD-4% και αυτό επιβεβαιώνεται από τη μέση τιμή της κατανάλωσης καυσίμου για CPSD-16%, η οποία είναι 0,78 τόνοι ανά διαδρομή. Από την άλλη η μέση τιμή της κατανάλωσης καυσίμου για CPSD-4% είναι υψηλότερη (0,87 τόνοι ανά διαδρομή). Η κατανάλωση καυσίμου επηρεάζεται από την επιλογή ταχύτητας, τον παράγοντα φορτίου και αυτός είναι ο λόγος για τον οποίο η κατανάλωση καυσίμου είναι υψηλότερη για CPSD-4% ενώ παράλληλα η μέση τιμή της ταχύτητας και του φορτίου είναι υψηλότερα για CPSD-4%. Η διακύμανση είναι παρόμοια και για τις δύο καταναλώσεις καυσίμου με τυπική απόκλιση 0,11 για CPSD-16% και 0,12 για CPSD-4%.

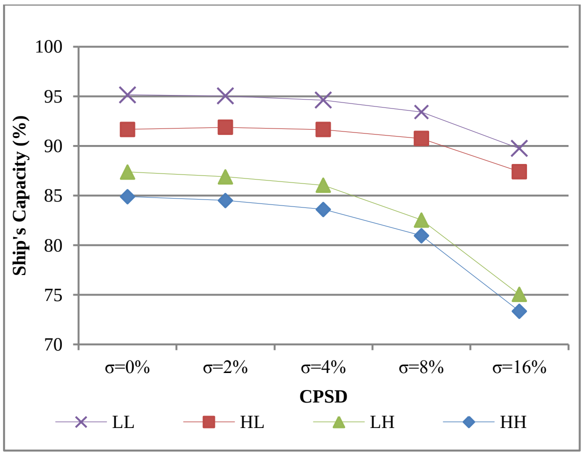


Σχήμα 5β Προφίλ κατανάλωσης καυσίμου για CPSD-4% και CPSD-16%, (L, L) σενάριο

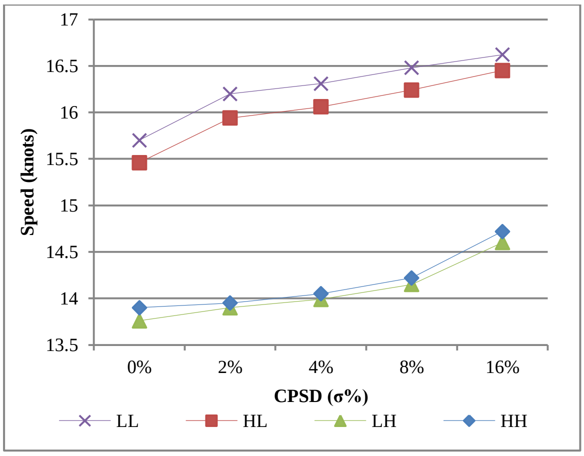
Αξιολόγηση της σημασίας των χαρακτηριστικών των παραγγελιών

Στην ενότητα αυτή παρουσιάζονται τα αποτελέσματα των πειραμάτων που πραγματοποιήθηκαν, με στόχο να αξιολογηθεί η σημασία των χαρακτηριστικών των παραγγελιών και πως αυτά ανταποκρίνονται στα 5 διαφορετικά "προφίλ" των συμβολαίων που μελετήθηκαν στην προηγούμενη ενότητα. Πιο συγκεκριμένα, θα αξιολογηθεί σε ποιο βαθμό α) το μέγεθος των παραγγελιών (V) και β) το μήκος της εμπορευματικής μεταφοράς των παραγγελιών (T) επηρεάζουν τον παράγοντα φόρτωσης, την ταχύτητα πλεύσης, το έσοδο, το κόστος και το συνολικό κέρδος της θαλάσσιας εμπορευματικής μεταφοράς.

Στο Σχήμα 6α, παρατηρούμε ότι η χωρητικότητα του πλοίου αξιοποιείται σε μεγαλύτερο βαθμό όσο α) το "προφίλ" των συμβολαίων καταγράφει μικρότερη διακύμανση, β) το μήκος ταξιδίου της παραγγελίας είναι μικρότερο, και γ) το μέγεθος της παραγγελίας είναι μικρότερο, καλύπτοντας βέλτιστα τους κενούς χώρους της υπολειπόμενης χωρητικότητα. Στο Σχήμα 6β, παρατηρούμε ότι η ταχύτητα πλεύσης αυξάνεται όσο α) το "προφίλ" των συμβολαίων καταγράφει μεγαλύτερη διακύμανση, β) το μήκος ταξιδίου της παραγγελίας είναι μικρότερο, γ) το μέγεθος της παραγγελίας είναι μικρότερο. Συμπερασματικά, το πλοίο καταγράφει μεγαλύτερη ταχύτητα πλεύσης όταν εκμεταλλεύεται καλυτέρα την χωρητικότητα του, εξυπηρετώντας περισσότερες παραγγελίες. Όσο περισσότερες παραγγελίες εξυπηρετεί, τόσο αυξάνεται και ο χρόνος φορτοεκφόρτωσης των παραγγελιών στα λιμάνια. Συνεπώς, το πλοίο αναγκάζεται να αυξήσει την ταχύτητα πλεύσης του ώστε να εξυπηρετήσει περισσότερες παραγγελίες και να αυξήσει τα έσοδά του.

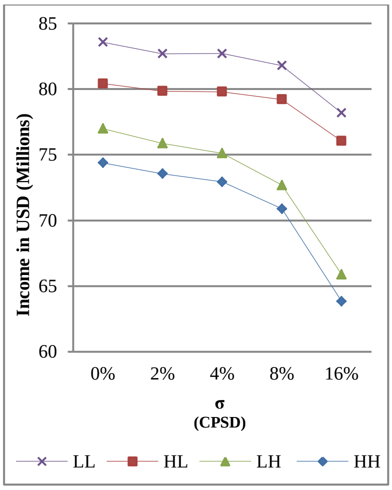


Σχήμα 6α Μέσες τιμές παράγοντα φόρτωσης των σεναρίων για όλα τα "προφίλ" συμβολαίων

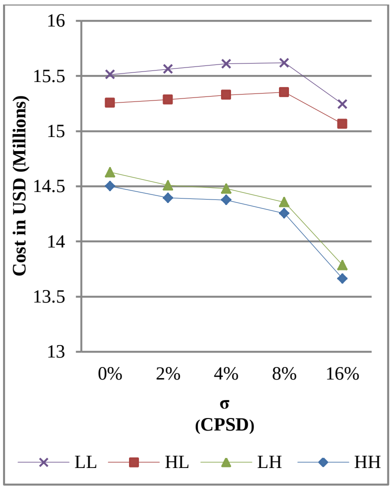


Σχήμα 6β Μέσες ταχύτητες πλεύσης των σεναρίων για όλα τα "προφίλ" συμβολαίων

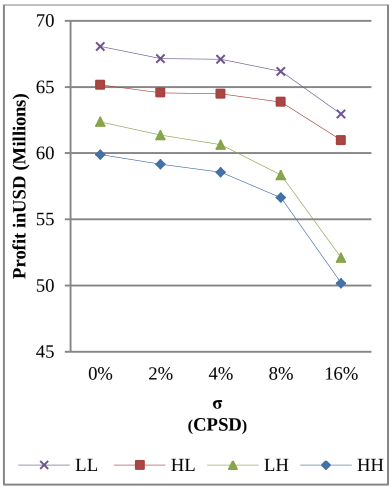
Τα Σχήματα 7α, 7β, 7γ παρουσιάζουν το μέσο έσοδο, το μέσο κόστος και το μέσο κέρδος των σεναρίων για όλα τα "προφίλ" συμβολαίων. Παρατηρούμε ότι οι τιμές του κέρδους ανταποκρίνονται με κοινό τρόπο στις μεταβολές α) του "προφίλ" των προϋπογεγραμμένων συμβολαίων, β) του μεγέθους των παραγγελιών (V) και γ) του μήκους της εμπορευματικής μεταφοράς των παραγγελιών (T). Αναλυτικότερα, στα σχήματα 7α και 7γ παρατηρούμε ότι τα έσοδα και τα κέρδη της εμπορευματικής μεταφοράς αυξάνονται όσο α) το "προφίλ" των συμβολαίων καταγράφει μικρότερη διακύμανση, β) το μήκος ταξιδίου της παραγγελίας είναι μικρότερο και γ) το μέγεθος της παραγγελίας είναι μικρότερο. Συμπερασματικά, το υψηλότερο έσοδο και κέρδος της εμπορευματικής μεταφοράς παρατηρείται στο σενάριο (L, L) , λόγω της ευελιξίας των παραγγελιών (καλύτερη εκμετάλευση της χωρητικότητας, με συχνότερες φορτοεκφορτώσεις), και το χαμηλότερο στο σενάριο (H, H), γεγονός που ήταν αναμενόμενο. Επιπρόσθετα, το έσοδο και το κέρδος είναι πιο ευαίσθητα στο μήκος της εμπορευματικής μεταφοράς παρά στο μέγεθος της παραγγελίας. Τέλος, όσον αφορά το κόστος της εμπορευματικής μεταφοράς παρατηρούμε ότι τα σενάρια με μικρότερο μήκος εμπορευματικής μεταφοράς παραγγελιών καταγράφουν μεγαλύτερο κόστος σε σχέση με αυτά με το μεγαλύτερο μήκος. Η συγκεκριμένη παρατήρηση θεωρείται λογική αφού, όπως προαναφέρθηκε, οι μικρού μήκους παραγγελίες οδηγούν σε αύξηση της ταχύτητα πλεύσης ώστε το πλοίο να εξυπηρετήσει περισσότερες παραγγελίες και να αυξήσει τα έσοδά της εμπορευματικής μεταφοράς που διεκπεραιώνει.



Σχήμα 7α Έσοδο των σεναρίων για όλα τα "προφίλ" συμβολαίων



Σχήμα 7β Κόστος των σεναρίων για όλα τα "προφίλ" συμβολαίων



Σχήμα 7γ Κέρδος των σεναρίων για όλα τα "προφίλ" συμβολαίων

Επίλογος

Στην παρούσα διπλωματική εργασία παρουσιάστηκε και μελετήθηκε το επιχειρηματικό μοντέλο ενός μεμονωμένου πλοίου τακτικής εμπορευματικής μεταφοράς, δεδομένου του δικτύου πλεύσης. Το εν λόγω επιχειρηματικό μοντέλο προσεγγίστηκε με τη δημιουργία ενός μαθηματικού μοντέλου μικτού ακεραίου προγραμματισμού. Το μαθηματικό μοντέλο συμπεριλαμβάνει όλες εκείνες τις σημαντικές αποφάσεις, οι οποίες αφορούν α) τη δημιουργία και δημοσίευση του αρχικού χρονοδιαγράμματος, λαμβάνοντας υπ' όψιν την προβλεπόμενη ζήτηση παραγγελιών καθώς και τα προϋπογεγραμμένα συμβόλαια, και β) την καταλληλότερη επιλογή των "πραγματικών" παραγγελιών που μεγιστοποιούν το κέρδος της εμπορευματικής μεταφοράς καθώς και τη δημοσίευση του τελικού χρονοδιαγράμματος. Η καινοτομία του εν λόγω μαθηματικού μοντέλου είναι η επιλογή των καταλληλότερων παραγγελιών που μεγιστοποιούν το συνολικό κέρδος της εμπορευματικής μεταφοράς, λαμβάνοντας υπ' όψιν α) την ταχύτητα πλεύσης, β) τον παράγοντα φόρτωσης και ταυτοχρόνως γ) την επιλογή των καταλληλότερων παραγγελιών.

Μία σειρά από πειράματα δημιουργήθηκε με σκοπό α) να εκτιμηθεί η σημασία της ομαλότητας του "προφίλ" των συμβολαίων, δηλαδή της χωρητικότητας που καταλαμβάνουν τα προϋπογεγραμμένα συμβόλαια στη συνολική χωρητικότητα του πλοίου, και β) να προσδιοριστεί το καταλληλότερο μέγεθος των παραγγελιών καθώς και το καταλληλότερο μήκος της εμπορευματικής μεταφοράς των παραγγελιών που επηρεάζουν τα οικονομικά δεδομένα και το χρονοδιάγραμμα του πλοίου. Αναλύοντας το "προφίλ" των συμβολαίων, διαπιστώθηκε ότι όσο πιο ομαλό είναι το "προφίλ" της χωρητικότητας που καταλαμβάνουν τα προϋπογεγραμμένα συμβόλαια, τόσο αυξάνονται και τα επίπεδα καλύτερης εκμετάλλευσης της συνολικής χωρητικότητας του πλοίου στην περίπτωση των σεναρίων (H, H) και (L, L). Όσον αφορά τα χαρακτηριστικά των παραγγελιών, η ευελιξία ενός (L, L) σεναρίου (μικρό μέγεθος παραγγελιών, μικρό μήκος εμπορευματικής μεταφοράς παραγγελιών) δίνει τη δυνατότητα στο πλοίο να εκμεταλλευτεί βέλτιστα τη χωρητικότητα του, αλλά και να επιλέξει υψηλότερες ταχύτητες πλεύσης. Από την άλλη, η δυσκαμψία που έχει το (H, H) σενάριο (μεγάλο μέγεθος παραγγελιών, μεγάλο μήκος εμπορευματικής μεταφοράς παραγγελιών) οδηγεί σε μικρότερη εκμετάλλευση της χωρητικότητας του πλοίου, αλλά και σε χαμηλότερες ταχύτητες πλεύσης. Τέλος, αξίζει επίσης να σημειωθεί ότι η προτιμότερη επιλογή είναι πρωτίστως το μικρό μήκος εμπορευματικής μεταφοράς μίας παραγγελίας και δευτερευόντως το μικρό μέγεθος της παραγγελίας.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Shipping industry

International trade is closely related to the global economy, environmental changes and politics (World Trade Organization, 2013).

The role of the sea shipping industry in international trade and global economy is critical, since merchant ships transported 155 million TEUs in 2012 and total shipments of petroleum products and gas products totaled 1.05 billions tons, where 289 millions tons came up from liquefied natural gas (LNG) and liquefied petroleum gas (LPG) (UNCTAD, 2013). Furthermore, sea transport is very cost effective. For example the cost of transporting a TEU carrying more than 20 tones from Asia to Europe equals to the value of an economy air ticket for the same journey (International Maritime Organization, 2012).

According to environmental changes, sea shipping accounts for 2.7 % of worldwide emissions. In 2011, the European Commission suggested that these emissions should be reduced by at least 40%, and if feasible by 50%, until 2050 (European Commission, 2014). Thus, significant changes need to be made in fuels, technology and operational practices (Psaraftis and Kontovas, 2013). There are several ways of reducing fuel consumption and CO_2 emissions, e.g. using different types of fuel, improving engine technologies, adjusting operational management, slow steaming etc. Reducing speed isn’t something new for the maritime transport at community. Significant work has focused on speed and emissions reduction. Slow steaming is an obvious step to fuel economy and to reduction of emissions. In practical terms, however, adjusting the shipping speed is an integrated problem that needs to consider order demand and profit maximization.

In practical terms, however, adjusting the shipping speed is an integrated problem that needs to consider order demand and profit maximization. The latter is highly relevant to scheduling of shipping, which is the topic of this thesis.

1.2. Operations planning in liner shipping

The maritime shipping industry may be classified into three main sectors (Lawrence, 1972): (a) liner shipping, (b) tramp shipping, and (c) industrial shipping. This work concerns the liner shipping sector, which may be further classified into short and deep sea shipping. Currently, there are more than 400 major liner shipping companies in operation (World

Shipping Council, 2014). Each of these companies operates a fleet of ships over a route network in order to support cargo among the network's ports using regular services operating under published timetables (Lun and Browne 2009).

Container liner shipping involves the transportation of containerized goods along scheduled service routes (Wang, 2013). Figure 1 depicts a typical liner route from Europe to Asia (Maersk, 2014).

Figure 1 A typical liner route from Europe to Asia (Maersk, 2014)

The container-ships used for this type of transport have a capacity that ranges between 7,500-18,500 TEUs (World Shipping Council, 2014). There are almost 4,900 container-ships operating globally, transporting approximately two-thirds of the value of total global trade (approximately goods that worth 4 trillion USD annually) (World Shipping Council, 2014). The global container fleet is about 34.5 million containers up until 2013 (World Shipping Council, 2014).

Operations planning in the liner shipping business is a multi-step process, and is depicted in Figure 2. The first step in this process is to design the shipping network (ports and routes to be served and approximate times of visiting these ports per route), and is carried out by experienced network designers (Agarwal and Ergun, 2008). It uses demand forecasting as well as pre-arranged contracts. In this process accurate demand forecasting is a competitive advantage (Plum, 2013). Overall network design is a problem of strategic importance, and affects significantly the company's profitability and success.

In the second step of Figure 1, the preliminary network is published in order to attract clients in addition to the long term contracts. These additional shipping orders are defined as spot orders (Hunter *et al*., 1993) and fill the remaining ship capacity.

Once the network is published, liner companies receive orders characterized by pick-up and delivery ports, order size (in TEUs) and time period. At this point, the company allocates ships into published routes (fleet management step of Figure 1). This step is highly dependent on the demand to be served.

The next step, assigns orders to the available ships that operate along the published routes. Based on order assignment (and the related loading and unloading time requirements), the detailed timetable of arrival and departure at each port is published. This detailed schedule is used in contractual arrangements, and drives vessel operations.

Figure 2 Liner shipping business model

1.3. Literature background in planning of liner shipping

Review studies regarding liner shipping status, and ship routing and scheduling include those of (Christiansen *et al*., 2004), and the recent study of (Christiansen *et al*., 2013), which overviews recent advancements in this area. These researches showed that although there is a high volume of papers related to the liner shipping sector many critical problems remain wide open and provide challenging opportunities for future research.

Several studies in this area have focused on topics related to the current thesis. According to (Tran and Haasis, 2014), we can categorize liner shipping into three major categories: (a) Container routing which involves optimal flow of laden and empty containers, (b) Fleet Deployment which involves ship assignment and ship scheduling, (c) Network Design which involves the selection of ports and their combination. We also assign papers with emphasis on fuel consumption and on CO_2 emissions into the fleet management category.

In the topic of cargo routing (Agarwal and Ergun, 2008) proposed an integrated mixed integer linear program to address the ship scheduling and the cargo routing problems simultaneously and their computational experiments indicate high percentage utilization on ship’s capacities and a significant number of transshipments. (Wang *et al*., 2013b) proposed an integer linear programming model to develop container paths with minimum costs in container routing. (Wang and Meng, 2012c) studied liner ship fleet deployment with container transshipment operations and showed that the optimal solution of the ship's utilization can be used to redesign liner services. (Yan *et al.*, 2009) proposed a model for short-term liner operations by using network flow techniques. The algorith was based on Lagrangian relaxation, a subgradient method, and a heuristic for the upper-bound solution, was developed to solve the model. The test results showed that the model and the solution algorithm could be useful references for ship scheduling and container shipment planning. (Bell *et al.*, 2011) transferred the classic frequency-based transit assignment method on containers assignment and the results showed a promising first step toward a global maritime container assignment model which represents the effects of sailing time, service frequency and port capacity on the pattern of full and empty container flows and therefore on port choice. (Wang and Tang, 2010) proposed an optimization model in order to maximize profit in container shipping based on chance constrained programming. The chance-constrained programming is translated into an integer programming and the variables include the number of heavy and empty containers shipped by lines, the shortage number of heavy containers, and the renting number of empty containers from requiring ports to meet the demand. The model can be used to optimize container shipping plan of sea carriage to a shipping company and get profit raise.

Fleet deployment – ship scheduling is the main interest of our literature review due to the similarity of our Thesis. (Fagerholt, 2004) proposed an integer program to minimize weekly operational costs for a considered fleet in a liner shipping network. The computational results show that proposed solution method is suitable for designing optimal routes in several liner shipping problems. Also, (Tirado *et al.*, 2013) proposed a dynamic and heuristic approach for routing in industrial shipping. Computational experiments show that the use of stochastic information within the proposed solution methods yields average cost savings of 2.5% on a set of realistic test instances. (Chen *et al.*, 2007) consider a container vessel scheduling problem with bi-directional flows and show that a special case of it is solvable as a linear program. (Wang *et al.*, 2013a) studied the case with transit-time-sensitive demand that is assumed to be a decreasing continuous function of transit-time. A mixed-integer nonlinear non-convex optimization model was first formulated to maximize the total profit of a ship route. Computational results based on a trans-Pacific liner ship route demonstrated the applicability and efficiency of the solution method. (Jepsen *et al.*, 2011) proposed a MIP model for minimizing the cost of ships and their fuel consumption in order to operate a green network. The proposed model reduces problem size using a novel aggregation of demands and a column generation approach for their solution. (Norstad *et al*., 2011) presented a multi-start local search heuristic for ship routing and scheduling by using speed as a decision variable. Computational results showed that the solution method solves problems of realistic size and that taking speed into consideration in tramp ship routing and scheduling significantly improves the solutions. (Karlaftis *et al*., 2009) were involved with routing with simultaneous pick-ups and deliveries with time windows solved using a hybrid genetic algorithm for establishing routes for a dedicated containership fleet. Their contribution was at the planning level as they extended previous work on routing of dedicated containership fleets and they developed and tested a metaheuristic algorithm tailored for the problem at hand. Minimization of fuel emissions through ship scheduling under uncertain port times have been studied by (Qi and Song, 2012). The general optimal scheduling problem was formulated and tackled by simulation-based stochastic approximation methods and were the first that proposed the problem of vessel scheduling along a fixed route in liner shipping under port uncertainty, with the objective of minimizing fuel consumption and emission, as well as the vessel delay penalty (Wang and Meng, 2012a) proposed a mixed-integer non-linear stochastic programming model to minimize fuel costs taking into consideration uncertainties at sea and at port Numerical experiments on real data provided by a global liner shipping company demonstrate that the proposed algorithm can efficiently solve real-case problems. A method for optimizing sailing speed in a liner shipping network in order to reduce the fuel consumption has been by (Wang and Meng, 2012b). The paper argues with researchers that use third power relationship and based on the historical data available propose that a more accurate function should be adopted. An algorithm for speed optimization problem to achieve fuel economy has been proposed by (Hvattum *et al*. 2013) and shows that optimal speeds can be found in quadratic time.

As far as the network design problem is concerned, (Kuroda *et al*., 2005a) presented a network model that considers the supply-demand international maritime transport market and evaluates the impact of introducing Post-Panamax ships. Findings of the different numerical examples based on application of proposed model suggest that the major use of Post-Panamax vessel leads to enforce the hierarchy between Asian ports. (Plum *et al*., 2014) proposed a branch and cut algorithm in order to solve the design of container shipping network. The developed solution method can solve problem instances with up to 25 ports, which makes it applicable to the design of real world intercontinental services. (Reinhardt *et al*., 2007) and (Reinhardt and Pisinger, 2012) have considered the combined fleet assignment and network design problem and proposed a mixed integer linear programming model that minimizes the overall cost. The contributions of these papers is a general formulation of the problem including transhipment and transhipment costs. A network design problem with fluctuating demand was quoted was formulated by (Chao, 2009) as a mixed integer problem the results show that the proposed model can provide a more realistic solution to the issues on the basis of changing demand and freight rates. (Sigurd *et al*., 2005) focused on the problem of designing a shipping network, between Rotterdam and several ports on the west coast of Norway and Rotterdam. This network that was serviced by newly built Ro-Ro ships (Sigurd *et al*., 2005). It was solved by a heuristic branch-and-price algorithm.

In the topic of CO_2 emission reduction which heavily interest us, (Armstrong, 2013) has discussed both technical and operational ways to reduce emissions in a theoretical level. (Corbett *et al*., 2009b) have proposed that a possible fuel tax in the order of 150$/ton would lead to an average speed, which, in turn, would lead to CO_2 emission reductions of about 20-30%. Slow steaming on a continuous basis has significant impact on fuel consumption and on CO_2 emissions (Cariou, 2011), but the speed limit does not automatically reduce the amount of CO_2 emitted on a global scale and should not be considered as a good short term measure in emissions reductions due to the side effects in society (Cariou and Cheiteau, 2012). Optimization of speed, in order to reduce emissions have been studied by (Fagerholt *et al.*, 2010) who have illustrated that slower steaming can lead to fewer emissions and propose an alternative solution methodology, in which the arrival times are discretized and the problem is solved as a shortest path problem on a directed acyclic graph. Extensive computational results confirm the superiority of the shortest path approach and the potential for fuel savings on shipping routes. Reduction of emissions and the fuel consumption savings through the reduction of speed have been studied by (Psaraftis *et al*., 2009) and (Psaraftis and Kontovas, 2009). However, a reduction in speed may have undesirable side-effects that may generally entail non-trivial costs. An implication on fast ships was conducted in order to identify alternatives that are more cost-effective and fleet size or alternatives ways to transport products that however do not solve the problem of total emissions committed in the way speed does. Reduction tactics show dramatic fuel savings and can be translated to significant emission reduction (Corbett *et al*., 2009a). (Du *et al*., 2011) have considered fuel consumption and ship emissions inside the berth while simultaneously retaining the service level of the terminal.

In Table 1, we classify selected liner shipping studies that contain mathematical models from the recent literature with respect to the topic of containerized liner shipping (Tran and Haasis, 2013), the objective function, and the major decision variables.

Table 1 Recent publications concerning container routing, fleet deployment/scheduling and network design problems

Author	**Container routing problem**	**Fleet / Scheduling problem**	**Network design problem**	**Objective function**	**Decision variables**		
					Speed	Spot orders[1]	Other
Agarwal and Ergun, 2008	✓	✓		MP[2]			*Weekly frequency, transporting cargo*
Bell *et al*., 2011	✓			MT[3]			*Container flow, service frequency*
Chao, 2009			✓	MP			*Ports, order of calling sequence, ship size, slot allocation, quantities handled*
Chen *et al*., 2007		✓		MV[4]			*Vessel loads, loads of empty containers and in inventory, vessels trips*
Jepsen *et al*., 2011			✓	MP			*Load and unload of containers, number of times the service sails*
Karlaftis *et al*., 2009		✓		MC[5]			*Vessel loads*
Kuroda *et al*., 2005			✓	MC			*Service frequency, vessel size*
Norstad *et al*., 2010		✓		MP	✓		*Weight on board ship, time for start of service*
Reinhardt *et al*., 2007		✓	✓	MC			*Amount of transshipment and of demand shipped*
Wang *et al*., 2013		✓		MP	✓		*Fleet deployment, Ship repositioning, Container transportation*
Meng and Wang, 2011		✓		MC			*Service frequency, containership deployment*
Wang and Meng, 2012b	✓	✓		MC	✓		
Wang and Meng, 2012c		✓		MC		✓	*Number of charted in and out ships, number of ships deployed on ship route*
Wang and Tang, 2010	✓			MP			*Heavy and empty containers, shortage number of heavy containers, and the renting of empty*

Ship Scheduling, Network Design and Cargo Routing have been profoundly investigated. However, a realist approach of profit maximization (spot and contract orders)

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[1] *Spot orders are not pre-arranged and can emerge by the time a ship departs*
[2] *MP: Maximize Profit*
[3] *MT: Minimize sailing Time*
[4] *MV: Minimize number of Ships*
[5] *MC: Minimize Cost*

and the cost minimization (fuel consumption based both on speed and load factor) in a realistic liner shipping network (where demand affects the ship scheduling) has not yet been published.

This thesis focuses on scheduling a single ship that operates in a liner shipping network. The aim is to maximize profit by selecting spot orders and sailing speed simultaneously. The spot order selection affects revenue and load factor (and thus fuel consumption), while speed selection affects fuel consumption. Ports sequence of visiting, vessel capacity constraints, total trip duration, speed limits, un/loading time and time windows inserted at each port (for the second part of the formulation) are taken under consideration. This problem is classified mainly into Fleet management- Ship scheduling category however it extends in issues of Cargo routing (loading and unloading operations) and Network Design (network initial timetable).

The remainder of this thesis is organized as follows. Section 2 provides a detailed problem description. Section 3 presents the new proposed model that addresses this problem. Section 4 presents an extensive experimental analysis that investigates the utilization of ship’s capacity and speed selection, the economical facts taken and the relationship between the size of a spot order, the trip length of a spot order, the load factor and the speed. Conclusions and recommendations for further study are included in Section 5.

2. Problem Definition

Taking under consideration the above business model of liner sea shipping in the present dissertation, we considered as given the sailing network and studied the case of one single vessel in a liner network. Therefore, the above mentioned business model was addressed in two phases, as presented in the following Figure 3.

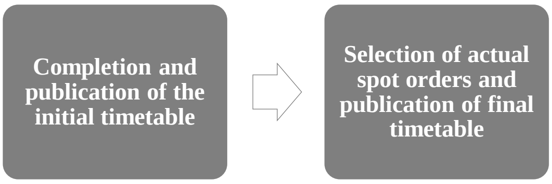

Figure 3 Approach of business model in liner shipping

Explicitly, in the first phase we consider as given the sailing network, which means the sequence of ports visiting, as well as the starting and ending time of service in the first and last port accordingly. Also, we consider as given both the results of forecasting demand in spot orders and the actual demand in pre-signed contracts. The mathematical model results in an initial timetable, which is published, in order to attract 'actual' spot orders. In the following Table 2 we illustrate a possible initial timetable given for Phase 1 based on the specifications of a liner shipping company.

Table 2 Initial timetable prototype of Phase 1

Ports	Arrives	Departs	Transit
1	*Monday*	*Wednesday*	-
2	*Saturday*	*Sunday*	6
3	*Tuesday*	*Wednesday*	9
4	*Sunday*	*Monday*	14
5	*Friday*	*Saturday*	19

Regarding the second phase of our mathematical model, by respecting the initial timetable, we get the final timetable that aims to maximize the freight transport profit, which is consisted of (a) the income from the contracted and the income of spot orders and (b) the fuel cost. According to income, we assume that it depends on the number of containers transported and the distance covered to delivery port. In the following Table 3 we illustrate a possible final timetable given for Phase 2 based on results (initial timetable) of Phase 1.

Table 3 Final timetable prototype of Phase 2

Ports	Terminal Name	Arrival Date	Departure Date	Voyage Number
1	Terminal A	*1 Sep 2014 08:00*	*3 Sep 2014 03:00*	001
2	Terminal A	*6 Sep 2014 11:15*	*7 Sep 2014 18:30*	002
3	Terminal B	*9 Sep 2014 06:40*	*10 Sep 2014 12:35*	003
4	Terminal A	*14 Sep 2014 17:00*	*15 Sep 2014 13:15*	004
5	Terminal C	*19 Sep 2014 20:35*	*20 Sep 2014 07:30*	005

The sailing cost[6] is related to fuel consumption, which, in turn, depends on sailing speed and the load level of the ship. The fuel consumption differs among ship types. The factors that affect the ship's fuel consumption include: (a) the Brake Specific Fuel Consumption (BSFC), (b) the load factor, (c) the design speed, (d) the operational speed, (e) the horsepower of the ship, (f) the distance travelled, and (g) the time the engines operates every day (Corbett *et al*., 2009b; Kontovas and Psaraftis, 2011). Considering that factors (a), (c), (e), (f) and (g) are constant in case of a liner ship, then optimizing the fuel consumption is related strictly to the operational speed (d) and the load factor (b). Factors (a) and (c) are constant for each vessel and alter by the engine type. Also we consider the time that the engines operate (g) is constant because the engines run 24 hours a day. In terms of other operating and non-operating costs, we make the simplified assumption that these are constant for a certain trip. We consider as given (a) the network that the vessel will operate, (b) the inter-port distances, (c) the total trip duration, (d) the charge price per TEU·nm, (d) the equation of fuel consumption, (e) the loading/unloading time at each port. For more detailed information see Appendix A. Finally, it should be mentioned that this study does not consider uncertain events, such as accidents, engine failures, delays due to weather conditions. The objective should be achieved considering (a) the ship's capacity (in TEUs), (b) the realistic speed limits, (c) the total trip duration, (d) the sequence of the visiting ports, and (e) the obligation of servicing contract orders.

At this point it is worth to mention that the scheduling process and the basic model assumptions have been discussed and validated by interviews taken by several shipping professionals and questionnaires given to 5 liner companies. This Appendix B contains the questionnaire. Important data were collected in order to understand the maritime shipping industry and the significance of vessel scheduling, speed optimization, emissions produced and eco-friendly shipping.

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[6] At first we estimate the fuel consumption and then we convert the fuel quantity consumed into fuel cost using the fuel price

3. The proposed model for liner ship scheduling and order selection

Our proposed mathematical model has been developed to address both phases of the planning process presented above. In the first phase, we use the model to construct an initial timetable providing the departure time from each port in order to optimize the profit functional based on forecasted spot order demand. In the second phase, the proposed model respects the initial timetable of the first phase, and considers actual spot order demand in order to optimize the profit functional.

In this section we develop a mixed-integer linear programming (MILP) model for the Scheduling and Order Selection Problem (SOSP) in liner shipping to address the aforementioned two phases. The notation, constraints, and objective function are discussed, followed by formulation discussion on model properties.

3.1. Notation

Let:

N	Set of ports
K	Set of discrete values k of sailing speed
L	Set of discrete values l of load level
Q	Total vessel's capacity
q_i	Vessel's quantity onboard when the ship departs from port i
p_i	Pickup contract quantities at port i
d_i	Delivery contract quantities at port i
W_i	Income earned from contract orders at port i
O	Set of spot orders
π_i^j	Pickup quantities at port i from spot order $j, j \in O$
δ_i^j	Delivery quantities at port i from spot order $j, j \in O$
r_j	Binary variable for selection spot order $j, j \in O$
Φ_j	Income from spot order $j, j \in O$
s_i	Start of service time at port i
t_{ikl}	Sailing time at port i with speed $k \in K$ and load level $l \in L$
C_{ikl}	Sailing cost at port i with speed $k \in K$ and load level $l \in L$
c	Rate of un/loading at port i, measured in TEU/day
a, b	Starting and ending date of trip
y_l	Low bound of load level l, measured in % load
u_l	Upper bound of load level l, measured in % load
BM	Big number, $BM >> 1$

Following the concept first presented by (Fagerholt *et al.*, 2010), we propose an alternative formulation that considers a discrete number of sailing speeds and capacity load levels. In order to formulate our problem, we let (a) N be the set of ports visiting, (b) K be the set that includes the discrete values of sailing speeds that the ship may select when moving from one port to the next one and (c) L be the set that includes the discrete values of load levels of the ship between ports. The level of each load factor defines a range of loads (y_l, u_l), with y_l the lower limit and u_l the upper limit of the range of load factor l.

Let the graph $G(E, A)$ be a graph with nodes $E = \{1, \dots, N\}$ that represent the ports of the liner route, and arcs $A = \{(i, i+1) | i = 1, \dots, N-1\}$ along the route, considering the pre-defined port sequence of the route.

Specifically, it may be noted that the trip should start after the predefined earliest departure time from port 1 and complete before the predefined latest arrival time at the last port N.

We assume that Q is capacity of the single ship and q_i the quantity of containers onboard when the ship departs from port i. The ship (a) has to serve all pre-signed contract orders and (b) select the most profitable spot orders at each port i. For the pre-signed contract orders, let p_i and d_i, be the total pickup and delivery quantities at each port i and W_i is the total income of contract orders serviced at port i. Note that d_1 and p_N, that is the delivery quantities at the first port and the pickup quantities at the last port are set to zero. According to spot orders, let O be the set of spot orders. Also, let π_i^j and δ_i^j be the pick up and delivery quantities of spot order $j \in O$, at each port i. Finally, let r_j be binary variables that receive the value of 1 if spot order $j \in O$ is served and zero otherwise. We assume that if a transportation spot order is selected then all the containers of the spot order should be transported. We define Φ_j as the income obtained by serving the selected spot order $j \in O$.

To model such constraints, we define variable s_i to be the time that service starts at port i. The binary variable $x_{ikl}, i = 1, \dots, N-1$ equals to 1 if the ship departs from port i with speed $k \in K$ and load level $l \in L$ and zero otherwise.

Furthermore, let t_{ikl} be the sailing time and C_{ikl} be the sailing cost at port i with selected speed $k \in K$ and load factor $l \in L$. We take under consideration the parameter c to represent the average time to load/unload one container from/to the ship at all ports. Sailing cost depends on the inter-port distance from port i to $i+1$, the sailing speed k selected, the load level l selected and the fuel price.

3.2. Model formulation for Phase 1

According to model formulation of Phase 1, the objective function aims to maximize the profit of liner shipping transportation service and consists of three terms: (a) the income from the contracted (b) the income of spot orders and (c) the fuel cost. Specifically, the first term refers to the total income from serving forecasted spot orders. Decision variable r_j ensures that only the income from the served spot orders will be accounted to the total income. The second term refers to the income that comes from total contract orders served at each port i. The third term defines the total fuel cost related to the sailing speed and the load factor between two sequential port and decision variable x_{ikl}.

$$max\, P = \sum_{j\in O} \Phi_j r_j + \sum_{i\in N} W_i - \sum_{l\in L}\sum_{k\in K}\sum_{i=1}^{N-1} C_{ikl} x_{ikl} \tag{1}$$

$$\sum_{l\in L}\sum_{k\in K} x_{ikl} = 1, \quad i = 1, \dots, N-1 \tag{2}$$

$$0 \le q_i \le Q, \quad i = 1, \dots, N \tag{3}$$

$$q_{i+1} - \sum_{j\in O} \left(\pi_{i+1}^j - \delta_{i+1}^j\right) r_j - \left(p_{i+1} - d_{i+1}\right) \; = q_i, \quad i = 1, \dots, N-1 \tag{4}$$

$$BM\left(1 - \sum_{k\in K} x_{ikl}\right) + y_l \le q_i \le u_l - BM\left(1 - \sum_{k\in K} x_{ikl}\right), \quad i = 1, \dots, N, k \in K, l \in L \tag{5}$$

$$s_i + \sum_{l\in L}\sum_{k\in K} t_{ikl} x_{ikl} + c\sum_{j\in O}\left(\pi_i^j + \delta_i^j\right) r_j + c\left(p_i + d_i\right) = s_{i+1}, \quad i = 1, \dots, N-1 \tag{6}$$

$$a \le s_1, \tag{7}$$

$$s_N \le b, \tag{8}$$

$$s_i \ge 0, \quad i = 2, \dots, N \tag{9}$$

$$r_j \in \{0,1\}, \quad j = 1, \dots, O \tag{10}$$

$$x_{ikl} \in \{0,1\}, \quad i = 1, \dots, N-1, k \in K, l \in L \tag{11}$$

Constraints (2) ensure that each port will be visited only once and that only one arc will be selected between two continuous ports. Constraints (3) safeguard that the number of containers onboard will not exceed the total ship capacity (Q). Constraints (4) define the number of containers (both contract orders and spot orders that have to be served) on the ship while it departs from port $i+1$. Constraints (5) define the load factor selected in order to estimate the right cost. We use a very big number BM>>1 in order to ensure that the load level will be selected by only by the selected forecasted spot orders. Constraints (6) ensure that the start of service at port $i+1$ equals the sum of the start of service of port i plus the time to complete the loading and unloading operations of both contract orders and forecasted spot orders at port i plus the time to travel from port i to port $i+1$ with the selected speed k and load level l. Constraints (7) and (8) ensure that the trip starts after the predefined earliest departure time from port 1 and completes before the predefined latest arrival time at the last port. Finally, constraints (9) to (11) define the permitted range of values of the decision variables.

3.3. Model adaptation for Phase 2

The solution of the model of Phase 1 will define the initial timetable (start of service time at each port). This timetable will be announced to the market in order to attract actual sport order demand. Thus, it imposes constraints on the decisions of Phase 2. As a result, the latter needs to consider the following: (a) actual spot orders, (b) all contract orders and (c) respect the start of service time at each port.

Thus, in the model of Phase 2, set O includes actual transportation spot orders $j \in O$. Similarly the actual spot orders are defined in the same way, where π_i^j and δ_i^j be the pick up and delivery quantities of the actual spot order $j \in O$, at each port i. Binary variable r_j is receiving the value of 1 if spot order $j \in O$ is served and zero otherwise. We also define Φ_j as the expected income obtained by serving the selected spot order $j \in O$.

Note that the quantity of contract orders at each port and the income that comes from these contract orders remains the same as in the first part of our model. That is, p_i and d_i, are again the pickup and delivery quantities related to the contract orders, and W_i is the related summed income at each port $i \in E$.

In order to give a flexibility in the selection process of speed and load (note that the forecasted spot orders may differ from the actual), but in the same time to respect the initial timetable (contract orders have specific dates of pickup and delivery), we use time margins at each port that allows us to alter our schedule and adjust in the real conditions of the trip. Considering that s_i is the time that service starts at port $i \in E,$ and in order to account for the time timetable of Phase 1, we introduce appropriate time windows per port $a_i \leq s_i \leq b_i$, where a_i is early edge of the time window and b_i be the late edge of the time window. The early edge a_i and the late edge b_i are set so that the vessel can arrive earlier or later than s_i which was the initial start of service at port i and realistic values are given to a_i and b_i (for example half a day earlier arrival and 1 day of delay).

Thus the problem of Phase 2 is formulated using the mixed integer-linear programming model of Phase 1 with the above mentioned sets, and replacing constraints (4) and (5) by the following one:

$$a_i \leq s_i \leq b_i, \quad i = 1, \dots, N \tag{12}$$

4. Experimental analysis

4.1. Complexity Analysis

The solution method is divided into three parts: (a) the solution method for the generation of contract orders (see Appendix C), (b) the solution method for mathematical model of Phase 1 and (c) the solution method for mathematical model of Phase 2. All experiments were implicated in Mathwork's Matlab 2014a combined with Gurobi optimizer 5.6.0 for Windows 32bit in a PC with Intel i5 CPU and 4GB RAM.

4.2. Experimental set up

We used the model of Chapter 3.2 and 3.3 in order to conduct an extensive experimental study. The objective of this study is to drill down and answer a series of interesting questions for the liner shipping problem under consideration.

These questions are the following:

(a) In what means does the variance of load profile of pre-singed contract orders influence the utilization of ship capacity, the sailing speed, and the fuel consumption?

(b) What type of spot orders to select in terms of order size and trip length to maximize income, profit?

(c) Which factors are statically related to sailing speed?

More specifically, our experiments have been conducted using a liner shipping scenario composed of two trip circles that includes 15 major ports per circle (see Figure 4). In order to simulate a deep sea shipping case we selected the sailing distances between consecutive ports randomly in the range between 1,500 and 2,500 nautical miles, using a uniform distribution.

We assumed that the total trip duration is 210 days in which the initial trip is repeated in a cycle twice. The loading/unloading time equals to 5,000 TEUs/day (Bryfors *et al*., 2006). For the Phase 2 of the problem, we have assumed that the width of the time window for the start of service at each port equals to two days, one day before and one day after the start of service time defined by the solution of Phase 1.

Figure 4 Possible network of 15 major ports in Europe, Asia and Africa

The characteristics of the vessel selected to navigate the route resemble those of Emma Maersk which is built in 2006, has 397m length and capable of safely carrying 156,907 DWT[7] of products which is translated to 15,000 TEUs total capacity. The parameters used in this scenario are presented in Table 4.

Table 4 Parameters used in the experimental analysis

Network	Number of ports per trip circle	15
	Number of trip circles	2
	Inter-port distance	1,500-2,500 NM
	Un/loading time	5,000 TEUs/day
	Trip duration	210 days
	Time window at each port	2 days
Ship	Selected ship	Emma Maersk
	Ship capacity	15,000 TEUs
Financial ratios	Income ratio	0.1$ per TEU-NM
	Fuel price	0.65 $/ lt
Speed	Range of speed	10-25 knots
	Discretization speed levels	16
Load factor	Range of load factors	0-100%
	Discretization levels of load factor	10
Demand	Demand of spot orders	217,500 TEU·ports /2 cycles
	Contract profile	50% (σ=0%, 2%, 4%, 8%, 16%)

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[7] DWT: Deadweight tonnage measures the vessel’s ability to transport weight

The fuel consumption of the vessel is estimated by applying the relationships proposed in the literature (Corbett *et al.*, 2009b; Kontovas and Psaraftis, 2011) taking under consideration each combination of sailing speed and load factor, as well as other parameters of Emma Maersk, provided in Appendix A.

The minimum sailing ship speed equals to 10 knots and the maximum equals to 25 knots. Furthermore, the load factor varies between 0 and 100% of total ship capacity. In each instance we assumed 16 discretization levels for the speed (10, 11, …, 25 knots), and 10 discretization levels for the load factor (10%, 20%, …, 100%). Fuel price equals to 0.64$ per liter (Bunker World, 2014) and the income was based on an average charge parameter of 0.1$ per TEU·NM (Brett, 2013).

Regarding contract orders, we have assumed that 50% of the ship's capacity is filled on the average by contract orders. For the experimental study we used various levels of the standard deviation parameter σ = 0%, 2%, 4%, 8%, 16% creating various demand profiles of contract orders. Especially, the variability of this utilization profile along the route is characterized by the standard deviation parameter σ. The actual capacity utilization profile for the contact orders is generated by a mixed integer program presented in Appendix B.

Regarding spot order demand, we have assumed a unit of measure. By this unit we measure the ports each order needs to cover from the pickup port to the delivery port (TEU·ports). We assume that the possible spot orders in total can fill up the remaining capacity of the ship, which means that the spot order demand is the vessel's half capacity (7,500 TEUs) multiplied by the possible pickup ports of the two trip cycles.

In order to investigate the effect of the spot order characteristics we considered the following two parameters: (a) the size of spot orders (V), in TEUs and (b) trip length of spot orders (T), in number of ports along the route. Spot orders are generated randomly by selecting the size and trip length from respective normal distributions. For each parameter (size or trip length) we assumed two levels: (a) High (H) and (b) Low (L). The parameters of the corresponding normal distributions for the two levels of each parameter are provided in Table 5.

Table 5 Characteristics of spot orders

Parameters	Label	Description
Size of spot orders (V)	High (H)	800 TEUs with σ equals to 200
	Low (L)	200 TEUs with σ equals to 50
Trip length of spot orders (T)	High (H)	11 ports with σ equals to 2
	Low (L)	2 ports with σ equals to 1

Taking into consideration the four different scenarios (V, T) regarding the spot orders (H, H),(L, H), (L, L), (H, L) and the five contract order profiles (CPSD-0%, 2%, 4%, 8%, 16%) mentioned above, there are $4 \times 5 = 20$ different cases to be examined (in the full factorial sense) as follows:

v. (H, H) Scenario: V=High, T=High for 5 different Contract Profiles
vi. (L, H) Scenario: V=Low T=High for 5 different Contract Profiles
vii. (L, L) Scenario: V=Low, T=Low for 5 different Contract Profiles
viii. (H, L) Scenario: V=High, T=Low for 5 different Contract Profiles

For each of the above 20 cased, we conducted 100 repetitions, for a total of 2,000 experimental instances.

4.3. In what means does the variance of load profile of pre-singed contract orders influence the utilization of ship capacity, the sailing speed, and the fuel consumption?

In the following Figures 5 and 6 are illustrated the results of one instance for the scenario (H, H) and in Figures 5 and 6 the results of one instance for the scenario (L, L), both for two different pre-signed contract profiles (CPSD-4%, CPSD- 16%), compared to the total vessel's capacity utilization and the sailing speed.

Figure 5 shows the results of one random instance for the (H, H) scenario and two different CPSD-4% and CPSD-16%. In both parts of the Figure the total profile rises gradually at the beginning of the trip (7 initial ports), and reduces gradually at the trip's end (7 latter ports). This reduction is because in the first ports occurs the loading of contract orders (that have priority compared to the spot orders) and, due to lack of time, we observe that there is not much loading regarding the spot orders (difference between the line of contracts and the line of contracts and spot orders). We also observe the same behavior in the final ports, where the vessel is forced to make only deliveries due to the trip length restriction and the upcoming trip end.

Comparing the Figures for the two CPSD levels, the total vessel load (contract and spot orders) is smoother in the low CPSD case (σ=4%), as expected (see Figure 5). Also, we see that the vessel's utilization is much better for the CPSD-4%. The proof lies in the average value of CPSD-4% that is 84%, when the average value of CPSD-16% is 73%. In the case of σ=16% (Figure 6), the variance of the total load is significantly higher. This variance is a result of the high deviation of the contract profile CPSD-16%.

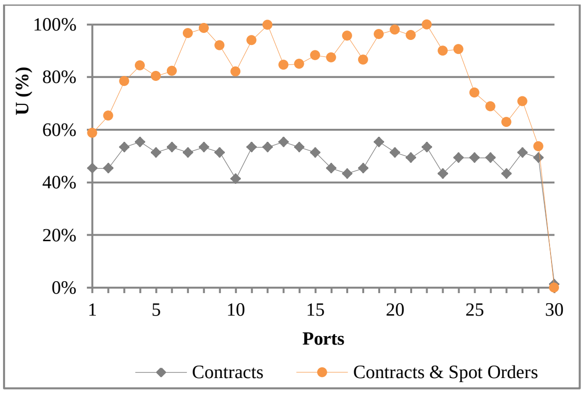

Figure 5 Utilization of ship's capacity for CPSD-4% in the *(H,H)* scenario

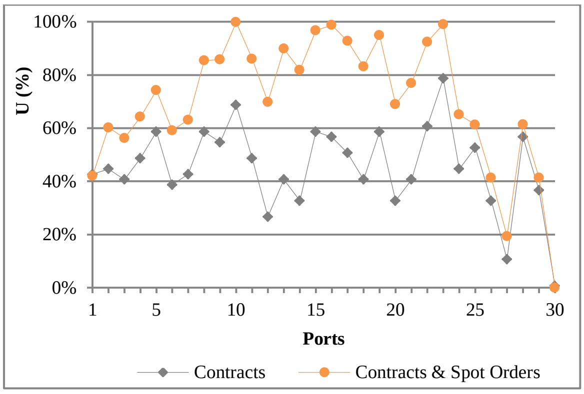

Figure 6 Utilization of ship's capacity for CPSD-16% in the *(H,H)* scenario

Figure 7 and Figure 8 show the vessel's utilization of one random instance for the (L, L) scenario and two different CPSD-4% and CPSD-16%. We also notice the same declinations in the beginning of the trip and at the end of it. However, due to the different trip length T this occurs for fewer ports compared to the (H, H) scenario. The load of total profile for CPSD-4% is smooth unlike the load of CPSD-16% that is not smooth. The variance of CPSD-16% is higher and this is the reason why we notice many declinations. The total profile (contracts and spot orders) is significantly higher for the lower value of CPSD-4%, as illustrated in Figure 7. The average value of both contracts and spot orders for CPSD-4% is 94% and the average value of total profile for CPSD-16% is 89%.

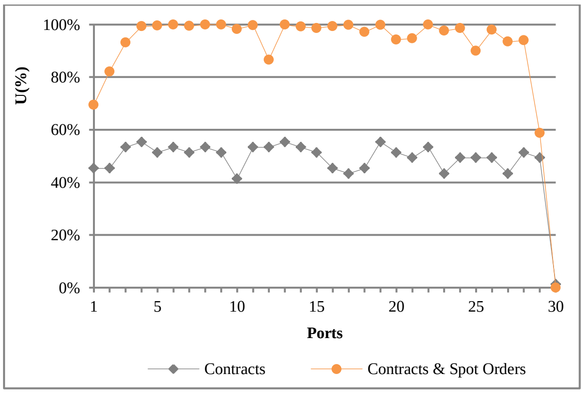

Figure 7 Utilization of ship's capacity for CPSD-4% in the *(L,L)* scenario

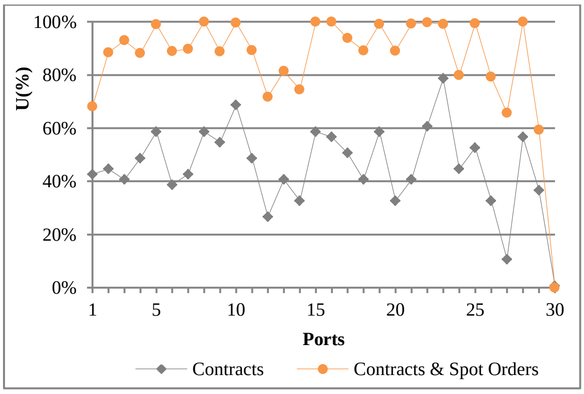

Figure 8 Utilization of ship's capacity for CPSD-16% in the *(L,L)* scenario

Therefore, as smoother is the profile of contract orders (CPSD), vessel's capacity utilization (U%) rises for both scenario (H, H) and scenario (L, L).

Regarding the sailing speed for the (H, H) scenario (Figure 9), it follows the smoothness of contract profile, which means that when CPSD is smooth (CPSD- σ=4%), the standard deviation of speed is nearly 0.83 knots, and when the contacts profile is uneven (CPSD- σ=16%), speed's standard deviation recorded is 2.15 knots. We notice that there is a big un-load at port 26 and a high load at port 27 and these force the vessel to speed up. The constraint of total trip duration and the time spent in un/loading procedures at those ports are responsible for the speed augmentation.

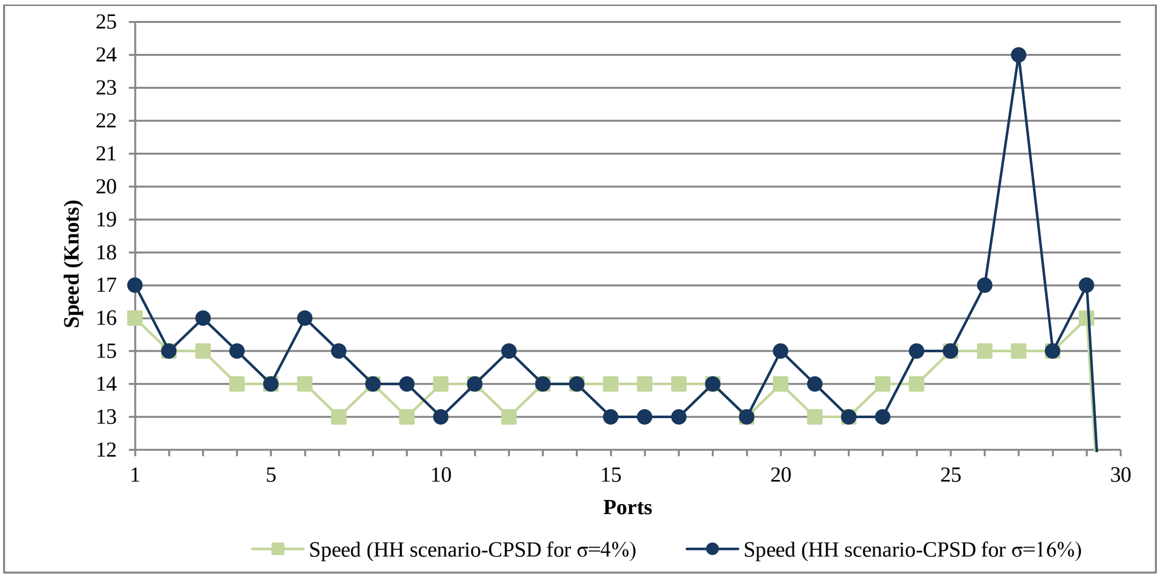

Figure 9 Speed profiles for CPSD-4% and CPSD-16%, *(H,H)* scenario

As far as the speed comparison in case of (L, L) scenario, the two speeds look almost identical with speed of CPSD-16% to be slightly lower. The average speed of CPSD-σ=16% is 16.2 knots and the average speed of CPSD-4% is 16.8 knots. Also, the standard deviation of speed for CPSD-4% is 0.87, when the standard deviation of CPSD-16% is 0.91. The fact that the ship transfers higher volume of TEU in CPSD-4% extrudes the ship to select higher speeds. Finally, the two high declinations observed at port 1 and at port 29 for both cases, are happening in order the ship to accomplish the un/loading procedures inside the time window given and the total duration of the trip accordingly.

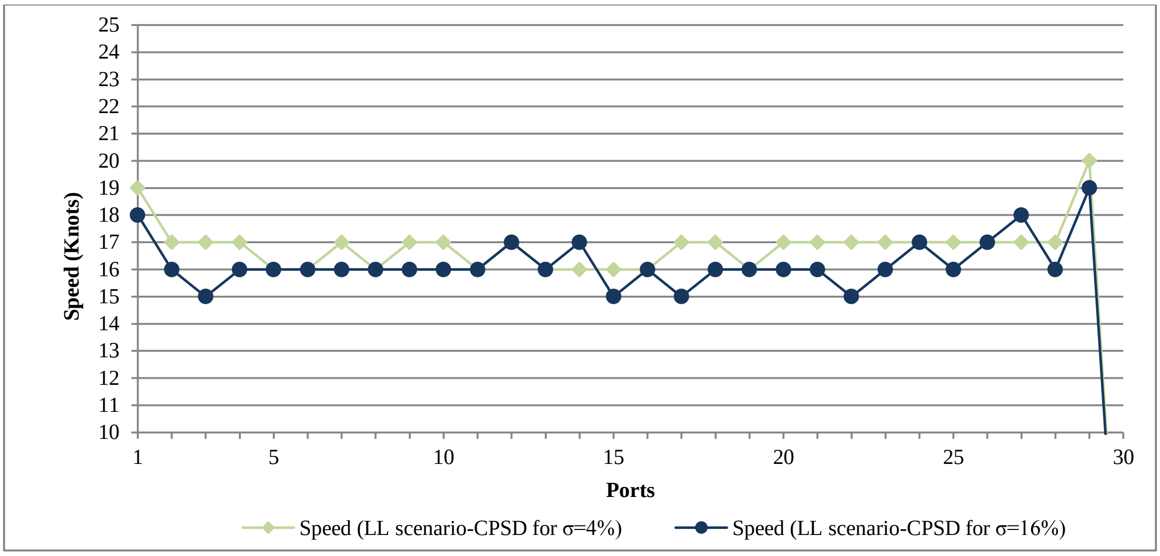

Figure 10 Speed profiles for CPSD-4% and CPSD-16%, *(L,L)* scenario

As far as the fuel consumption of (H,H) scenario of CPSD-16% appears to be lower and more stable compared to the fuel consumption of CPSD-4%. The average value of fuel consumption for CPSD-16% is 0.72 tons per route with a standard deviation of 0.10. On the contrary the average value of fuel consumption for CPSD-4% is 0.8 tons per route and a standard deviation equal to 0.11. The results are considered to be expected because both mean values of speed and load are higher for CPSD-4%.

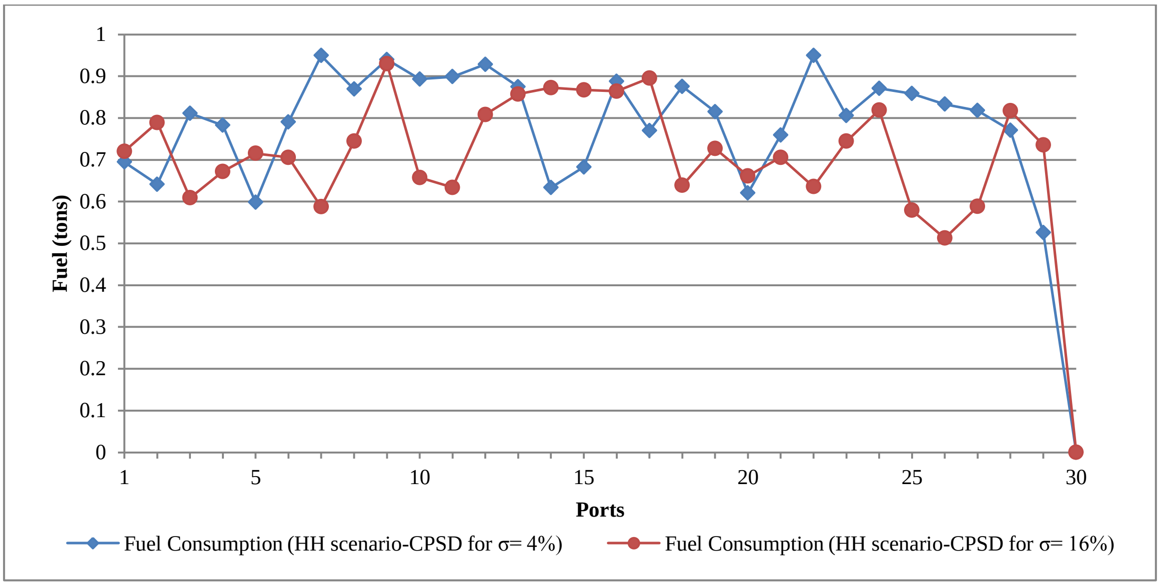

Figure 11 Fuel consumption profiles for CPSD-4% and CPSD-16%, *(H,H)* scenario

Regarding (L, L) scenario, fuel consumption of CPSD-16% appears to be lower compared to the fuel consumption CPSD-4% and can be confirmed by the average value of fuel consumption for CPSD-16%, which is 0.78 tons per route. On the other hand the average value of fuel consumption for CPSD-4% is higher (0.87 tons per route). Fuel consumption is affected by the speed selection the load factor and this is the reason why the fuel consumption is bigger for CPSD-4% when the average value of speed and load are bigger for CPSD-4%. The variance is similar for both fuel consumptions with standard deviation 0.11 for CPSD-16% and 0.12 for CPSD-4%.

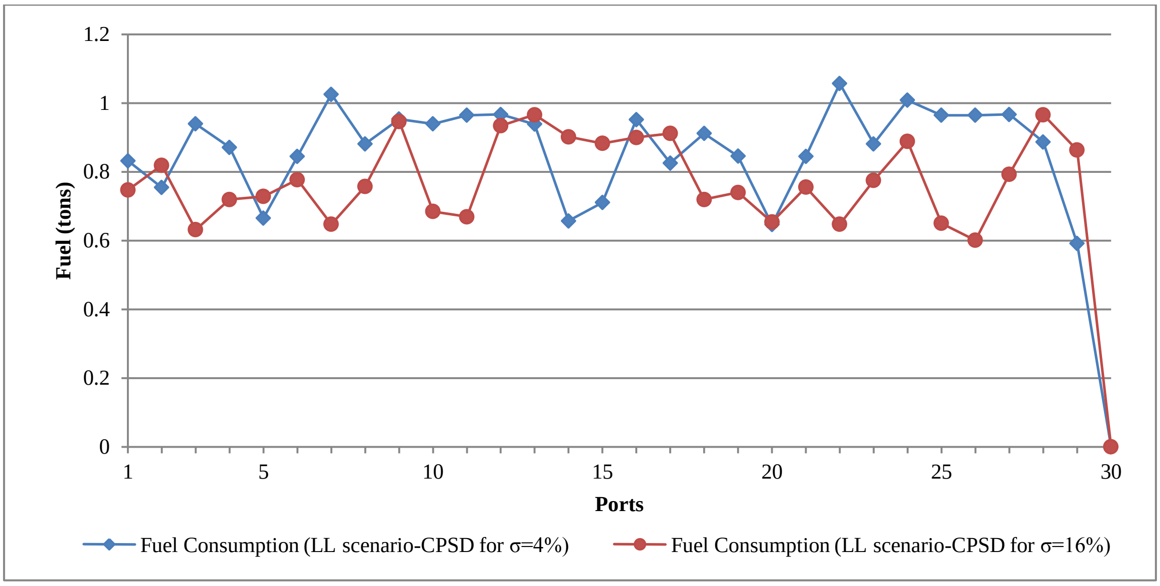

Figure 12 Fuel consumption profiles for CPSD-4% and CPSD-16%, *(L,L)* scenario

4.4. What type of spot orders to select in terms of order size and trip length to maximize income, profit?

In this section, are presented the results of the experimental analysis that was conducted in order to evaluate the significance of the spot orders characteristics and how they are corresponding into the five different contract profiles that were studied in the previous section. More specifically, is going to be evaluated to what extend a) the size of spot orders (V) and b) the trip length of the freight transport for spot orders (T) influence the load factor, the sailing speed, the income, the cost and the total profit of the shipping transportation.

Figure 13 presents the vessel’s utilization for all scenarios and all CPSD’s. According to Figure 13, we notice that in all scenarios the load has the trend to decline as the CPSD is increasing. However, the scenarios with high size (V) are more sensitive to CPSD. As the CPSD rise, the scenarios with high size (V) are more sensitive compared to the scenarios with low size V and the load is better for low size (V). Figure 14 presents the mean speeds for all scenarios and CPSD's. The mean speeds' follow the same trends but the sensitivity differs by the size of order (V). The mean speeds of low size (V) scenarios are increasing more as (highly sensitive) the CPSD is rising when at the same the high size (V) scenarios follow the same trend but with less sensitivity.

As a result, vessel records higher sailing speed when it exploits best the vessel's capacity utilization by servicing more spot orders. The more spot orders the vessel services, the more is the un/loading time spent at ports. Therefore, the vessel is forced to increase the sailing speed in order to service more spot orders and increase the income levels.

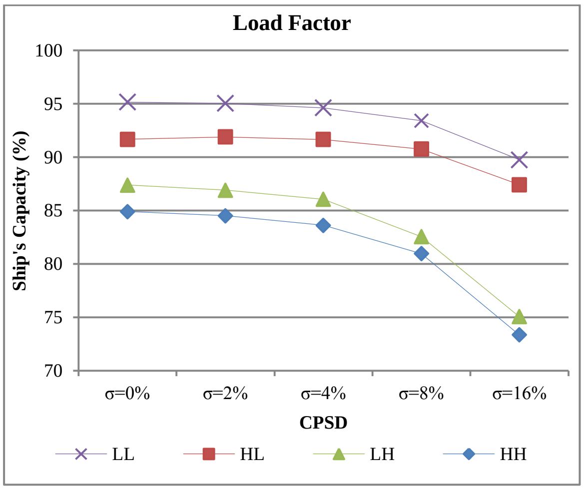

Figure 13 Mean Load factors as a function of CPSD for all scenarios

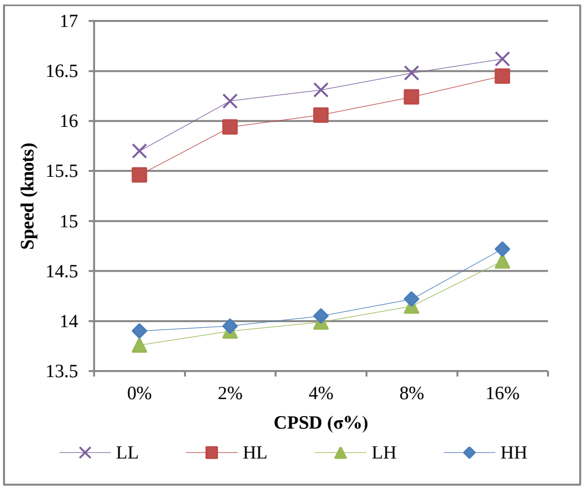

Figure 14 Mean Speeds for all scenarios and CPSD for all scenarios

Figures 15, 16, 17, present the mean income, the mean cost and the mean profit for all scenarios and contact profiles (CPSD). We notice that the values of income correspond in the same manner in the variations of a) the profile of pre-signed contracts (CPSD), b) the size of spot orders (V) and c) the trip length of spot orders (T). More explicitly, in Figures 15, 17 we observe that both income and profit rise when: a) CPSD records smaller deviation, b) the trip length for spot orders is lower and c) the size of spot orders is lower. In conclusion, the higher income and profit of this freight transport is spotted in the (L, L) scenario due to flexibility (better utilization of vessel's capacity, with more frequent un/loading procedures) and the lower is potted in the (H, H) scenario, fact that was expected. Additionally, income and profit are more sensitive in the trip length of spot orders (T), rather that the size of spot orders (V). Finally, as far as the cost we notice that scenarios with lower trip length indicate higher cost compared to the scenarios with higher trip length of spot orders. This observation, is considered logical because, as mentioned before, low trip length spot orders results to the increase of sailing speed so that the vessel shall service more spot orders and increase the income of the freight transport that carries through.

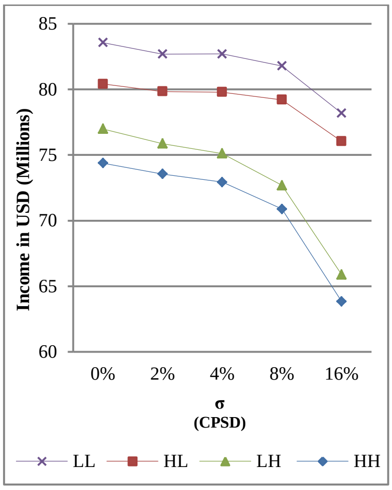

Figure 15 Income of each scenario for different CPSD

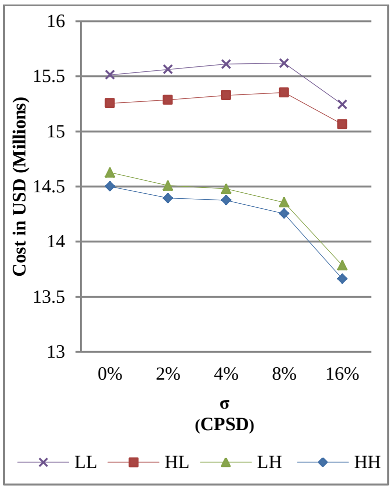

Figure 16 Cost of each scenario for different CPSD

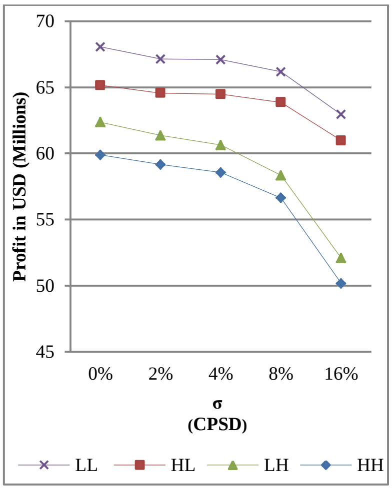

Figure 17 Profit of each scenario for different CPSD

4.5. Which factors are statically related to sailing speed?

The significance of the three factors contract profile standard deviation (CPSD), size of spot orders and length of trip of spot orders (V, T) on income and speed (and thus fuel cost and the profit functional) has been validated through Analysis of Variance. A two sample T-test was conducted and all calculations were performed by using the Minitab 17 Analysis Software. Table 6 shows that only trip length (both high and low) affects on speed and not the size of order neither the CPSD.

Table 6 Statistical Significance

Factors	p value	Mean	Standard Deviation
(T)=*High Trip length*	0	13.67	2.71
(T)=*Low trip length*		16.38	3.68
(V)=*High size*	0.890	15.07	3.36
(V)=*Low size*		14.98	3.24
$CPSD$-4%	0.969	M=15.03	SD=3.29
$CPSD$-16%		15.04	SD=3.31

5. Conclusions

In the present thesis it was presented and studied the business model of one single vessel that transacts a liner freight transport in a considered as given network. The above business model was approached by creating a mathematical model based on mixed integer linear programming. The mathematical model includes all the important decisions that refer to a) the completion and publication of the initial network taking under consideration the forecasted demand of spot orders and pre-signed contracts, b) the optimal selection of 'actual' spot orders that maximizes profit of this freight transport as well as the publication of the final timetable. The novelty of this mathematical model is the selection of the most profitable spot orders that maximize total profit taking under consideration a) the sailing speed, b) the load factor and simultaneously, c) the selection of the optimal spot orders.

A series of experiments was conducted in order to a) evaluate the importance of 'smoothness' of contract profiles, meaning the capacity that contract profiles occupy in the total vessel's capacity, and b) to define the optimal size of spot orders as well as the trip length of spot orders in this freight transport that influence the economical data and the vessel's timetable. Explicating the contract profile, it was determined that a 'smooth' profile in pre-signed contracts, results to the increase of utilization levels of total vessel's capacity in the (H, H) and (L, L) scenarios. Regarding the spot orders' characteristics, the flexibility of the (L, L) scenario (low size of spot orders, low trip length of spot orders in the freight transport) permits the vessel to optimally exploit its capacity and simultaneously select higher sailing speeds. On the other hand, the rigidity of the (H, H) scenario results in lower vessel utilization and lower selection of sailing speeds. Also, it is worth mentioning that the most preferable selection is primarily the low trip length in the freight transport and secondarily the low size of spot orders.

Finally, we should highlight that future research must be conducted in the liner shipping problems. The new environmental policies will affect the industry of liner shipping. Green liner shipping should be considered as the next direction of research where both operational and technologic solutions can be given. Finally, factors like weather conditions and market factors highly affect a vessel's schedule and profitability and should be considered important as well.

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Appendix A: Ship characteristics and fuel consumption functions

Emma Maersk is powered by a Wartsila-Sulzer 14RTFLEX96-C engine (BSFC[8]=171g/kWh) (WARTSILA, 2014). The engine is capable of 109,000 horsepower (81MW) and of burning 3,600 US gallons (14,000 lt) of heavy fuel oil per hour. Also, she has five diesel generators (Caterpillar 8M32 auxiliary engines) that together can produce 27,893 horsepower (20.8 MW). (BSFC=178g/kWh) (Caterpillar Marine, 2013). The design at sea speed is 25.5 knots. We do not consider some of the technologies that the ship is using, like exhaust heat recovery and cogeneration. By these systems, some of the exhaust gases are returned to the engine, so as to improve economy and to lower emissions. Fuel consumption for vessels, in general, is given by the following function (Corbett *et al*., 2009b):

$$F_{ijk} = \left[MF_k\left(\frac{s_{1k}}{s_{0k}}\right)^3 + AF_k\right]\left(\frac{d_{ij}}{24s_{1k}}\right),$$

Variables	Description
i, j	Origin and destination port
k	Individual vessel serving ij route
F_{ijk}	Fuel consumption per trip
MF_k	Main engine(s) daily fuel consumption
AF_k	Auxiliary engine(s) daily fuel consumption
s_{1k}, s_{0k}	Operational speed and design at sea-speed of vessel respectively in units of nautical miles (nm) per hour
d_{ij}	Distance between two ports (nm)
MF_k, AF_k	Determined by the power of the vessel, fuel consumption rates (g/kWh) and engine load factors

Additionally, to estimate the fuel consumption per engine, which we do not know, we use the following function (Kontovas & Psaraftis, 2011):

$$FC\left(\frac{t}{day}\right) = BSFC\left(\frac{g}{kWh}\right) \times 10^{-6}\left(\frac{t}{g}\right) \times L(\%) \times P(kW) \times t(h) \times 24(\frac{h}{day})$$

Variables	Description
FC	Fuel consumption of each engine both main and auxiliary
$BSFC$	Break specific fuel consumption is equal to fuel consumption divided to the power installed (it depends on the type of engine)
L	Load factor
t	Time
P	Power

---

[8] BSFC: Break Specific Fuel Consumption is a measurement unit of fuel efficiency

Appendix B: Questionnaire

A. Company profile

Company name:
………………………………………………………………………………………………
Country:
………………………………………………………………………………………………
E-mail:
………………………………………………………………………………………………

i. **What is the range of transportation your company provides?**

1. International
2. National
3. Both

ii. **What kind of shipping company are you? (you can choose more than one category)**

1. Short Sea Shipping

Handy Size	Coastal	Mini Bulker	Feeder Vessel	Other……………………

2. Deep Sea Shipping

Handy Max	RO-RO	Containership	Tanker	Other……………………

iii. **What kind of transport service your company provides?**

1. Scheduled transportation service at full cargo/ container
2. Scheduled transportation service at less than full cargo/ container
3. Non-scheduled transportation service at full cargo/container
4. Non-Scheduled transportation service at less than full cargo/ container
5. Other. Please define:
………………………………………………………………………………………………

iv. **What kind of goods are you transporting?**

1. Dry bulk cargo
2. Liquid bulk cargo
3. Containers
4. Other. Please define:
………………………………………………………………………………………………

B. General information about routing

i. Scenario Short Sea Shipping

- Fill in the starting point, the intermediate ports visited and the last port for a possible route

Starting-Port: ……………………………………………………………………………………
Destination-Port: ……………………………………………………………………………………
Number of Stops: ……………………………………………………………………………………
Intermediate Ports: ……………………………………………………………………………………

- Reasons for stopping. Tick inside the box. Importance:
  1.Very Low, 2.Low, 3.Medium, 4.High, 5.Very High

a) Necessary refueling

1	2	3	4	5

b) Known demand

1	2	3	4	5

c) Scheduled transshipments

1	2	3	4	5

d) Handling tariffs

1	2	3	4	5

e) Environmental motivations (for example: inland sub-shipping due to emissions)

1	2	3	4	5

f) High quality services (for example: delivery in a time window, intact commodity etc.)

1	2	3	4	5

g) Other. Please define:
……………………………………………………………………………………

ii. Scenario Deep Sea Shipping

- Fill in the starting point, the intermediate ports visited and the last port for a possible route

  Starting-Port: ……………………………………………………………………………………
  Destination-Port: ……………………………………………………………………………………
  Number of Stops: ……………………………………………………………………………………
  Intermediate Ports: ……………………………………………………………………………………

- Reasons for stopping. Tick inside the box. Importance:
  1. Very Low, 2.Low, 3.Medium, 4.High, 5.Very High

a) Necessary refueling

1	2	3	4	5

b) Known demand

1	2	3	4	5

c) Scheduled transshipments

1	2	3	4	5

d) Handling tariffs

1	2	3	4	5

e) Environmental motivations(for example: inland sub-shipping due to emissions)

1	2	3	4	5

f) High quality services (for example: delivery in a time window, intact commodity etc.)

1	2	3	4	5

g) Other. Please define: ……………………………………………………………………………………

iii. Scenario Asia to Europe

- Fill in the starting point, the intermediate ports visited and the last port for a possible route

Starting-Port: ………………………………………………………………………………………

Destination-Port: ………………………………………………………………………………………

Number of Stops: ………………………………………………………………………………………

Intermediate Ports: ………………………………………………………………………………………

- Reasons for stopping. Tick inside the box. Importance:
  1.Very Low, 2.Low, 3.Medium, 4.High, 5.Very High

a) Necessary refueling

1	2	3	4	5

b) Known demand

1	2	3	4	5

c) Scheduled transshipments

1	2	3	4	5

d) Handling tariffs

1	2	3	4	5

e) Environmental motivations(for example: inland sub-shipping due to emissions)

1	2	3	4	5

f) High quality services (for example: delivery in a time window, intact commodity etc.)

1	2	3	4	5

g) Other. Please define: ………………………………………………………………………………………

C. Speed selection

i. Selection of optimal speed
Tick inside the box. Importance:
1.Very Low, 2.Low, 3.Medium, 4.High, 5.Very High

1. Demand

1	2	3	4	5

2. Product type

1	2	3	4	5

3. Vessel type

1	2	3	4	5

4. Emissions reduction

1	2	3	4	5

5. Other. Please define:
……………………………………………………………………………………………

ii. Does your company use speed optimization as a fuel economy solution?

1. Yes (If you choose yes please circle the following questions)

   Used mainly on:
   - a) Deep sea Shipping
   - b) Short sea Shipping
   - c) Both

   Achievement of speed optimization
   - a) Predefined reduced speed (stabilized percentage)
   - b) Dynamic speed optimization depending on the route's needs
   - c) Predefined optimized reduced speed selection per trip

2. No

iii. When did you start on planning optimizing the chosen speed?

1. More than five years ago
2. One year ago
3. Not until no

D. Green shipping

i. Adopting an eco-friendly approach would be better for:

Tick inside the box. Importance:
1.Very Low, 2.Low, 3.Medium, 4.High, 5.Very High

1. Marketing reasons

1	2	3	4	5

2. Emissions reduction

1	2	3	4	5

3. Fuel economy

1	2	3	4	5

4. Forward thinking company

1	2	3	4	5

ii. How do you plan on reducing CO2 emissions?

1. Speed optimization

1	2	3	4	5

2. New vessels

1	2	3	4	5

3. Different selection of fuel

1	2	3	4	5

4. Other. Please define:
…………………………………………………………………………………………......

iii. Would you use methanol as a fuel in the future?

1. Yes
2. No
3. Maybe

iv. How do you estimate the emissions related to your ships?

1. Methodologies (actual standards, guidelines, schemes)
2. Calculation tools (software, algorithm)
3. Databases (commercial or public databases in which there are collected CO_2 emissions data)
4. Other. Please define:
   ……………………………………………………………………………………………...

v. Would you install EGCS in the future? (exhaust gas cleaning system)

1. Yes
2. No
3. Maybe

vi. Would you install Aerofoil technology in the future?

1. Yes
2. No
3. Maybe

Appendix C: Selecting contracts to simulate the contract profile

In order to simulate the contract profile in our experimental analysis, we model the problem of Contract Profile with Standard Deviation (CPSD) as a mixed integer linear problem. The CPSD is actually the number of TEUs that we want to transport between ports through contract orders. Initially, we define the CPSD that we want to use (for example 40% of vessel's capacity and σ=5%). Afterwards, we create this profile using the normal distribution along the ports. In order to achieve the CPSD we create a big number of contracts orders. Then, we select those contract orders that can reach closely to the CPSD target that we want to achieve.

The quantity of contract orders and the trip length of contract orders are generated using the uniform distribution. The quantity of contract orders is 300-3,000 TEUs and the contract order trip length is 1-10 ports.

Let:

O	Set of contract orders j
$\bar{q}_i$	Contract Profile in TEU for port $i = 1, \dots, N-1$
q_i	Contract Profile from selected contract orders that are being served at port $i = 1, \dots, N-1$
Q	Vessel's capacity
p_i^j	The pickup quantity of TEU at port $i = 1, \dots, N$ of $j \in O$ order
d_i^j	The delivery quantity of TEU at port $i = 1, \dots, N$ of $j \in O$ order
r_j	Binary variable which refers to the selection of contract orders $j \in O$

Let $\bar{q}_i$ be the CPSD that we want to achieve at port $i = 1, \dots, N-1$. Let $q_i, i = 1, \dots N-1$ be the total quantity of TEUs from the contract orders selected at port i. We consider that q_i refers to the total number of TEUs from contract orders that are being serviced at port i, which are the contract orders that already have been picked up (at a previous port) or are being picked-up at port i minus the contract orders delivered. Also let O be the set of possible contract orders. Let $r_j, j \in O$ be the decision variable for contract order selection; where r_j takes the value 1 if the contract order is selected or the value 0 if not. …. Let p_i^j, d_i^j, the pickup and delivery quantities at port $i = 1, \dots N$ for contract orders $j \in O$ at port $i = 1, \dots N$. Note, that p_N^j and d_i^j are zero because the vessel can not pickup contract orders from the last port nor deliver ports at the first. Finally, let Q be the total ship's capacity.

$$min \sum_{i \in N} \bar{q}_i - q_i \qquad \text{(A-1)}$$

Objective function (A-1) minimizes the difference between the target contract profile wanted and the one created from the selected contract orders.

$$\bar{q}_i - q_i \geq 0, \quad i = 1, \dots, N \qquad \text{(A-2)}$$

$$\sum_{j \in O} (p_i^j + d_i^j) r_j \geq 0, \quad i = 1, \dots, N \qquad \text{(A-3)}$$

$$q_{i+1} - \sum_{j \in O} (p_{i+1}^j - d_{i+1}^j) r_j = q_i, \quad i = 1, \dots, N-1 \qquad \text{(A-4)}$$

$$0 \leq q_i \leq Q, \quad i = 1, \dots, N \qquad \text{(A-5)}$$

$$r_j \in \{0,1\}, \quad j = 1, \dots, O \qquad \text{(A-6)}$$

Constraint (A-2), ensures us, that the profile selected will not exceed the initial expectations. Constraint (A-3), ensures us that the orders selected will not be zero. Constraint (A-4), define the number of containers served at port $i + 1$ (pickup and delivery) and the contract orders carried after the service time at port will be equal to those served at port i. Finally constraints, (A-5) and (A-6) safeguard that the selected contract profile quantity will not exceed the ship capacity and that decision variable r_j is 0 or 1 depending on the contract orders' selection.