National Technical University of Athens
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Ph.D. Dissertation

Model development for the optimization of network operation in the aftermath of a catastrophic event

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Abstract

Although not at the forefront of emergency management rationale, in cases of catastrophes, transportation networks prove their role as vital lifelines, ensuring network connectivity and providing the necessary, underlying ways for the execution of a series of emergency operations. At the same time, transportation networks are themselves vulnerable to structural and functional degradation, which, combined with the stochasticity involved in the travelers' behavior and the diverse needs arising under emergency conditions, mount the pressure for the need of effective network management; this will, most probably than not, require a re-structuring of network functioning, often in the form of network re-configuration, along with the employment of other operational strategies. In this context, the development of appropriate management tools that can account for the network's operational state and the individuals' behavioral aspects and optimally re-structure them to the benefit of overall network functionality are of significant practical importance. In such settings, these tools can help facilitate the related emergency operations and provide critical added value to the whole disaster management process.

In this context, the present thesis endeavors to advance the state-of-the-art in disaster management by providing a framework that supports and promotes the enhancement of network functionality in an integrated manner. The thesis distances itself from the consideration of specific network operations and examines network functioning from a wider perspective, that of generalized network management. In order to do so, the framework explicitly considers the operational state of the network and users' behavioral patterns and attempts a system re-organization on the basis of defined objectives; this is achieved through the use of appropriate strategies, the development of a multi-aspect performance measure, the formulation of suitable hypotheses regarding route construction and route choice and the selection of an appropriate analysis concept. The dissertation ultimately provides a sound conceptual and mathematical framework for efficiently handling the various needs arising in the period following a catastrophe. The framework can be used as a planning tool by transportation professionals and stakeholders and adds a higher degree of realism in the decision-making process by explicitly accounting for some of the stochasticities that are either way present in transportation management, but possibly exacerbated in a post-disaster setting.

Εκτεταμένη περίληψη

ΕΠ.1 Αντικείμενο έρευνας και μεθοδολογικά βήματα

Παρότι δεν βρίσκονται στο επίκεντρο του σχεδιασμού διαχείρισης έκτακτων καταστάσεων, σε περίπτωση καταστροφικών γεγονότων, ο ρόλος των μεταφορικών δικτύων είναι ζωτικής σημασίας καθώς εξασφαλίζουν συνδεσιμότητα μεταξύ των γεωγραφικών περιοχών και παρέχουν το απαραίτητο, υποκείμενο υπόβαθρο για την εκτέλεση έκτακτων επιχειρήσεων. Ταυτόχρονα, τα μεταφορικά δίκτυα είναι και τα ίδια τους ευάλωτα σε δομική και λειτουργική υποβάθμιση, ενώ η στοχαστικότητα που χαρακτηρίζει τη συμπεριφορά των χρηστών και οι διαφορετικές ανάγκες που προκύπτουν ως απόρροια των καταστροφικών γεγονότων αυξάνουν την ανάγκη για αποτελεσματική διαχείρισή τους. Κάτι τέτοιο, σε γενικές γραμμές, προϋποθέτει την αναδιαμόρφωση της λειτουργίας του δικτύου, συχνά με τη μορφή του επανασχεδιασμού αυτού, σε συνδυασμό με την αξιοποίηση άλλων στρατηγικών διαχείρισης. Κατά συνέπεια, η διαμόρφωση κατάλληλων εργαλείων διαχείρισης που θα μπορούν να συνυπολογίσουν τη λειτουργική κατάσταση του δικτύου και τις διαφορετικές συμπεριφορές των χρηστών και να τις αναδιοργανώσουν με βέλτιστο τρόπο προς όφελος της συνολικής λειτουργικότητας του δικτύου κρίνεται ως μεγάλης πρακτικής σημασίας. Υπό τέτοιες συνθήκες, τα εργαλεία αυτά θα μπορούν να διευκολύνουν τις σχετικές έκτακτες επιχειρήσεις και να προσδώσουν προστιθέμενη αξία στην όλη διαδικασία διαχείρισης καταστροφών.

Πράγματι, η κοινωνική εξέλιξη δημιουργεί την ανάγκη θέσπισης και εφαρμογής αποτελεσματικών μέτρων αντιμετώπισης των καταστροφικών γεγονότων ούτως ώστε να διατηρείται η κοινωνική δομή, συνοχή και λειτουργία. Σε αυτό το πλαίσιο, η παρούσα διδακτορική διατριβή εστιάζεται στη διαχείριση καταστροφών σε μεταφορικά δίκτυα στην περίοδο που έπεται του καταστροφικού γεγονότος. Παρότι πλήθος επιχειρήσεων μπορούν να λάβουν χώρα στη μετα-καταστροφική περίοδο (με την εκκένωση δικτύου να είναι πιθανώς η πλέον σημαντική και εκτενώς μελετημένη μεταξύ αυτών εξαιτίας της σημασίας της για την προάσπιση της ανθρώπινης ζωής και υγείας), η διδακτορική διατριβή εστιάζεται στο αντικείμενο της γενικευμένης διαχείρισης δικτύου. Προς το σκοπό αυτό, από τη μία λαμβάνονται υπ' όψιν οι ανάγκες που διαμορφώνονται από διαφορετικούς τύπους χρηστών μέσω της θεώρησης κινήσεων και προς στις δύο κατευθύνσεις κυκλοφορίας, ενώ από την άλλη εφαρμόζονται κατάλληλες στρατηγικές διαχείρισης και μέτρα απόδοσης σε σχέση με τους οριζόμενους για το σύστημα στόχους. Παράλληλα ενσωματώνονται και συμπεριφορικά χαρακτηριστικά των χρηστών σε όρους επιλογής διαδρομής.

Η διαχείριση δικτύου, όπως διαμορφώνεται μέσα από τις σχετικές επιχειρήσεις που πραγματοποιούνται σε αυτό, μπορεί γενικά να θεωρηθεί ως μία περίπτωση του προβλήματος σχεδιασμού δικτύου (network design problem (NDP)), ενός από τα πλέον δύσκολα προβλήματα στο αντικείμενο του σχεδιασμού των μεταφορών. Εξ' ορισμού, το πρόβλημα του σχεδιασμού δικτύου περιλαμβάνει αποφάσεις που σχετίζονται με τις στρατηγικές διαχείρισης που θα εφαρμοστούν στο δίκτυο για τη βελτιστοποίηση της απόδοσής του, ενώ παράλληλα συνυπολογίζει τυχόν περιορισμούς στον προϋπολογισμό που διατίθεται καθώς και τη συμπεριφορά των χρηστών κατά τη διαδικασία επιλογής διαδρομής. Η βελτίωση της απόδοσης του δικτύου επιδιώκεται μέσω του επανασχεδιασμού αυτού ή / και της ανακατανομής της ζήτησης ενώ η συμπεριφορά των χρηστών αποδίδεται μέσω των αρχών της αιτιοκρατικής (deterministic user equilibrium (DUE)) ή της στοχαστικής ισορροπίας του χρήστη (stochastic user equilibrium (SUE)). Παρ' όλ' αυτά, η αιτιοκρατική ισορροπία του χρήστη θεωρείται ανεπαρκής για τη μοντελοποίηση της συμπεριφοράς των μετακινούμενων, ειδικότερα δε κατά τη διάρκεια εκτάκτων περιστάσεων. Πράγματι, οι διακυμάνσεις των φόρτων που παρατηρούνται ως αποτέλεσμα αλλαγών στην προσφορά και τη ζήτηση οδηγούν στο συμπέρασμα πως τα στοχαστικά μοντέλα ισορροπίας είναι μάλλον καταλληλότερα για την απόδοση προβλημάτων του πραγματικού κόσμου. Ωστόσο, και παρά την ευελιξία των προβλημάτων σχεδιασμού δικτύου να ενσωματώσουν τυχαίες μεταβλητές στη διατύπωσή τους, οι έως τώρα ερευνητικές προσπάθειες σε στοχαστικά προβλήματα είναι εξαιρετικά περιορισμένες.

Ως εκ τούτου, η παρούσα διδακτορική διατριβή στοχεύει στην εξέλιξη της έως τώρα έρευνας στο αντικείμενο της διαχείρισης καταστροφικών γεγονότων υιοθετώντας μία ολοκληρωμένη προσέγγιση για την ενίσχυση της λειτουργικότητας του δικτύου με εξέταση του ευρύτερου φάσματος της λειτουργίας αυτού. Το πλαίσιο που διαμορφώνεται με αυτόν τον τρόπο λαμβάνει υπ' όψιν του τόσο τη λειτουργική κατάσταση του δικτύου όσο και τα πρότυπα συμπεριφοράς των χρηστών και επιχειρεί μία αναδιοργάνωση του συστήματος στη βάση συγκεκριμένων στόχων: αυτό επιτυγχάνεται μέσω της χρήσης κατάλληλων στρατηγικών διαχείρισης, της ανάπτυξης ενός πολυ-παραγοντικού μέτρου απόδοσης, της διαμόρφωσης κατάλληλων υποθέσεων σε σχέση με την αντίληψη των πιθανών διαδρομών και της επιλογής αυτών από τους μετακινούμενους και της χρήσης του κατάλληλου είδους ανάλυσης. Η διδακτορική διατριβή εν τέλει εισηγείται ένα ολοκληρωμένο εννοιολογικό και μαθηματικό πλαίσιο για την αποτελεσματική διαχείριση των αναγκών που προκύπτουν σε ένα μεταφορικό δίκτυο στην περίοδο που έπεται ενός καταστροφικού γεγονότος. Το πλαίσιο μπορεί να χρησιμοποιηθεί ως μέθοδος σχεδιασμού από τους εμπλεκομένους φορείς και υποδεικνύει μία ρεαλιστικότερη προσέγγιση επί του προβλήματος, με ρητή θεώρηση ορισμένων από τις στοχαστικότητες που εκ των πραγμάτων υπάρχουν στη διαχείριση μεταφορικών δικτύων αλλά συχνά εντείνονται στο μετα-καταστροφικό περιβάλλον. Ως εκ τούτου, η διδακτορική διατριβή προάγει τις αντίστοιχες ερευνητικές προσπάθειες, οι οποίες, σε γενικές γραμμές έως τώρα, αποφεύγουν να εντάξουν παραμέτρους στοχαστικότητας στις διατυπώσεις των προβλημάτων σχεδιασμού δικτύου.

Σε αντιστοιχία με τον ερευνητικό σκοπό, τα μεθοδολογικά βήματα που ακολουθούνται στην παρούσα διδακτορική διατριβή μπορούν να συνοψιστούν ως εξής:

- Εκτενής ανασκόπηση της βιβλιογραφίας στον τομέα της διαχείρισης καταστροφών με έμφαση στα αλληλο-σχετιζόμενα αντικείμενα της εκτίμησης της απόδοσης δικτύου και του σχεδιασμού εκτάκτων επιχειρήσεων. Στόχος είναι ο προσδιορισμός των πλέον πρόσφατων εξελίξεων στα ανωτέρω πεδία καθώς και των ερευνητικών περιοχών που προσφέρουν δυνατότητες περαιτέρω διερεύνησης.

- Σύνοψη των υφιστάμενων μοντέλων επιλογής διαδρομής και των μεθόδων σχεδιασμού διαδρομής. Στόχος είναι η παροχή του απαραίτητου υπόβαθρου για την επιλογή του καταλληλότερου συνδυασμού των παραπάνω παραμέτρων σε σχέση με τα χαρακτηριστικά του μετα-καταστροφικού περιβάλλοντος και των στόχων σχεδιασμού.
- Ανάπτυξη ενός ολοκληρωμένου εννοιολογικού πλαισίου με ενσωμάτωση ποικίλων πτυχών του προβλήματος της γενικευμένης διαχείρισης δικτύου. Στόχος είναι η διαμόρφωση μίας θεωρητικής και μεθοδολογικής βάσης για το σχεδιασμό εκτάκτων επιχειρήσεων έπειτα από καταστροφικό γεγονός ικανοποιώντας το γενικευμένο στόχο της ενίσχυσης της απόδοσης του δικτύου.
- Διατύπωση των μαθηματικών μοντέλων που αντιστοιχούν στο εννοιολογικό πλαίσιο που διαμορφώθηκε. Στόχος είναι η σύνθεση των εκφράσεων που αποτυπώνουν τη θεωρητική σύλληψη του μοντέλου και αποτελούν την ουσία της έρευνας που πραγματοποιήθηκε.
- Δημιουργία αποτελεσματικών αλγορίθμων βελτιστοποίησης για την επίλυση των μαθηματικών μοντέλων που δημιουργήθηκαν. Στόχος είναι η κατάλληλη χρήση ισχυρών μεθοδολογιών επίλυσης (όπως οι μεθευρετικοί αλγόριθμοι) που μπορούν να μειώσουν τον υπολογιστικό φόρτο που σχετίζεται με τα προβλήματα διαχείρισης δικτύου ενώ παράλληλα παρέχουν αποτελέσματα υψηλής ποιότητας και ευρωστίας.
- Επιβεβαίωση της εγκυρότητας και της αποτελεσματικότητας του εννοιολογικού πλαισίου, των μοντέλων σχεδιασμού και των αλγορίθμων επίλυσης που διαμορφώθηκαν μέσω της εφαρμογής τους σε δίκτυα δοκιμών υπό διαφορετικά σενάρια καταστροφών και ποικιλία υποθέσεων αναφορικά με τις παραμέτρους του προβλήματος.

Συμπερασματικά, η διδακτορική διατριβή συνεισφέρει μία καινοτόμα και δομημένη προσέγγιση στο αντικείμενο της διαχείρισης μεταφορικού δικτύου έπειτα από καταστροφικό γεγονός, ξεκινώντας από την εννοιολογική σύλληψη και τη μαθηματική διατύπωση ενός ενοποιημένου πλαισίου και συνεχίζοντας με τη δημιουργία εξελιγμένων μεθοδολογιών επίλυσης και την εφαρμογή αυτών σε δίκτυα δοκιμών προκειμένου να εξακριβωθεί η αποτελεσματικότητά τους.

ΕΠ.2 Διάρθρωση διδακτορικής διατριβής

Αναλυτικότερα, η διδακτορική διατριβή διαρθρώνεται ως εξής:

- Στο *πρώτο* κεφάλαιο δίδεται ο ορισμός των εννοιών της καταστροφής και της διαχείρισης καταστροφών μέσα από διαφορετικές προσεγγίσεις της βιβλιογραφίας και παρουσιάζεται ο ρόλος των μεταφορικών δικτύων στην όλη διαδικασία σχεδιασμού. Παράλληλα αναλύεται ο σκοπός της εκπονούμενης έρευνας και τα μεθοδολογικά βήματα που ακολουθούνται προς αυτή την κατεύθυνση ενώ επιπλέον παρατίθεται η διάρθρωση και η περιγραφή των περιεχομένων στη διδακτορική διατριβή κεφαλαίων.
- Το *δεύτερο* κεφάλαιο αναλύει το πρόβλημα της διαχείρισης καταστροφικών γεγονότων από τη σκοπιά των μεταφορικών δικτύων. Γίνεται διαχωρισμός μεταξύ του σχεδιασμού

κατά τη διάρκεια της περιόδου που προηγείται ή έπεται της καταστροφής, τονίζοντας τη σημασία της δεύτερης περιόδου και των αντίστοιχων ενεργειών στη διασφάλιση της καθολικής λειτουργικότητας του δικτύου. Σε αυτό το πλαίσιο, ο μετα-καταστροφικός σχεδιασμός διαχωρίζεται και μελετάται στη βάση δύο διακριτών υπο-προβλημάτων: (α) της εκτίμησης της απόδοσης του δικτύου, και (β) του καθορισμού των σχετικών εκτάκτων επιχειρήσεων που θα λάβουν χώρα στο δίκτυο και του σχεδιασμού αυτών. Πραγματοποιείται εκτενής βιβλιογραφική ανασκόπηση των δύο αλληλο-σχετιζόμενων αντικειμένων, με περαιτέρω επεξήγηση και ανάλυση των επιμέρους χαρακτηριστικών τους. Η βιβλιογραφία αναφορικά με την απόδοση του δικτύου αναλύεται σε όρους: (α) του θεωρούμενου καταστροφικού περιβάλλοντος, και (β) της ακολουθούμενης εννοιολογικής προσέγγισης. Ο πρώτος όρος αναλύεται περαιτέρω στον τύπο της καταστροφής, στα χαρακτηριστικά του δικτύου και στους μηχανισμούς αστοχίας των επιμέρους στοιχείων που λαμβάνονται υπ' όψιν. Ο δεύτερος όρος αναφέρεται στον ακολουθούμενο τύπο της ανάλυσης, στα χρησιμοποιούμενα μέτρα απόδοσης, στις υπάρχουσες αλληλο-εξαρτήσεις μεταξύ των μελών του δικτύου, στις εφαρμοζόμενες πριν ή μετά την καταστροφή παρεμβάσεις και στους στόχους που τίθενται. Από την άλλη, η βιβλιογραφία στο αντικείμενο του σχεδιασμού των εκτάκτων επιχειρήσεων κατηγοριοποιείται σε όρους: (α) σκοπού, και (β) διαδικασίας σχεδιασμού. Ο πρώτος αναφέρεται στο είδος των επιχειρήσεων που πραγματοποιούνται στο δίκτυο καθώς και στο χρόνο σχεδιασμού και εφαρμογής τους, ενώ ο δεύτερος εστιάζει στην πραγματική διαδικασία λήψης αποφάσεων και περιλαμβάνει τις καθοριζόμενες δραστηριότητες, τα χρησιμοποιούμενα εργαλεία ανάλυσης, τις προσδιοριζόμενες στρατηγικές και παραμέτρους καθώς και τους στόχους που τίθενται.

- Το *τρίτο* κεφάλαιο εστιάζει στο πρόβλημα του καταμερισμού της κυκλοφορίας στο δίκτυο και προσφέρει μία επισκόπηση των μοντέλων επιλογής διαδρομής και των μεθόδων δημιουργίας του συνόλου αυτών. Συγκεκριμένα, εξαιτίας της διαμόρφωσης του προβλήματος της μετα-καταστροφικής διαχείρισης δικτύου ως προβλήματος σχεδιασμού δικτύου, και με δεδομένη την ανεπάρκεια της αρχής της αιτιοκρατικής ισορροπίας του χρήστη να αποδώσει ρεαλιστικά τη συμπεριφορά των μετακινούμενων (ιδιαίτερα σε έκτακτες περιστάσεις), έχουν αναπτυχθεί μοντέλα επιλογής διαδρομής που βασίζονται σε διατυπώσεις τύπου logit ή probit. Παρά το γεγονός ότι και οι δύο κατηγορίες έχουν τη βάση τους στη θεωρία της χρησιμότητας υπάρχουν διακριτές διαφορές μεταξύ τους που καθιστούν τα χαρακτηριστικά των μοντέλων που ανήκουν στην εκάστοτε κατηγορία περισσότερο ή λιγότερο επιθυμητά κατά τη διαδικασία της μοντελοποίησης της επιλογής διαδρομής. Στο κεφάλαιο παρουσιάζονται το πολυωνυμικό μοντέλο logit (multinomial logit model (MNL)) καθώς και τα περισσότερα από τα μοντέλα που ανήκουν στην οικογένεια του MNL, ενώ τα υπόλοιπα μοντέλα που βασίζονται στο MNL και τα μοντέλα τύπου probit περιγράφονται στο Παράρτημα Α. Επίσης, στο κεφάλαιο παρατίθενται μαθηματικές διατυπώσεις της στοχαστικής ισορροπίας του χρήστη. Το κεφάλαιο καταλήγει με την περιγραφή τόσο των έμμεσων όσο και άμεσων μεθόδων δημιουργίας ενός συνόλου διαδρομών, με τις άμεσες μεθόδους (από τις αιτιοκρατικές και τις στοχαστικές μεθόδους που βασίζονται στη συντομότερη διαδρομή έως τις μεθόδους περιορισμένης απαρίθμησης και τις πιθανοτικές) να αναλύονται περισσότερο εκτενώς.

- Στο *τέταρτο* κεφάλαιο πραγματοποιείται η εννοιολογική σύλληψη και διαμόρφωση του μοντέλου που χρησιμοποιείται για τη βελτιστοποίηση της λειτουργίας του δικτύου έπειτα από καταστροφικό γεγονός. Το μοντέλο διατυπώνεται ως ένα μικτό πρόβλημα σχεδιασμού δικτύου (mixed network design problem (MNDP)): δύο διακριτές στρατηγικές διαχείρισης (η αναστροφή των λωρίδων κυκλοφορίας και η ρύθμιση της ζήτησης), ένα πολυ-παραγοντικό μέτρο απόδοσης (με συνδυασμό δεικτών χρόνου διαδρομής, ικανοποίησης της ζήτησης και προσβασιμότητας μεταξύ των ζευγών προέλευσης - προορισμού), ο καταμερισμός της κυκλοφορίας στο δίκτυο σύμφωνα με την αρχή της στοχαστικής ισορροπίας του χρήστη (ακολουθώντας το μοντέλο paired combinatorial logit (PCL)) και η επαναλαμβανόμενη δημιουργία διαδρομών (σύμφωνα με τη μέθοδο της επιβολής ποινής στους συνδέσμους του δικτύου (link penalty approach)) συνδυάζονται υπό το πλαίσιο της ανάλυσης τρωτότητας προκειμένου να αποδώσουν ένα επανασχεδιασμένο δίκτυο με ανακατανεμημένη ζήτηση με στόχο τη μεγιστοποίηση της απόδοσής του. Στο κεφάλαιο περιγράφονται τα βασικά σημεία του προβλήματος σε συνδυασμό με τη μαθηματική του έκφραση ενώ η συζήτηση επί των επιμέρους πτυχών του προβλήματος υποστηρίζει τις σχετικές υποθέσεις που έγιναν και τις αποφάσεις που ελήφθησαν. Στο τέλος του κεφαλαίου παρουσιάζεται ένα λεπτομερές διάγραμμα εργασιών των προγραμματιστικών βημάτων του μοντέλου όπως αυτά υλοποιήθηκαν στο υπολογιστικό περιβάλλον του λογισμικού πακέτου MatLab.
- Το *πέμπτο* κεφάλαιο αναλύει τη μεθοδολογία επίλυσης του προβλήματος που υιοθετήθηκε. Εξαιτίας της δομής του μοντέλου διαχείρισης ως μικτού προβλήματος σχεδιασμού δικτύου (δι-επίπεδη διατύπωση με συμπερίληψη τόσο συνεχών όσο και διακριτών μεταβλητών), η κυρτότητα του χώρου των λύσεων δεν εξασφαλίζεται. Ως εκ τούτου, η χρήση μεθοδολογιών επίλυσης που προϋποθέτουν και εξασφαλίζουν ακρίβεια έπρεπε να αποκλειστεί, με συνακόλουθη προσφυγή σε προσεγγιστικούς ή μεθευρετικούς αλγόριθμους προκειμένου να προκύψουν λύσεις πρακτικής αξίας. Σε αυτό το πλαίσιο, το εν λόγω πρόβλημα επιλύεται με το συνδυασμό ενός γενετικού αλγόριθμου (genetic algorithm (GA)) με μία διαδικασία καταμερισμού της κυκλοφορίας στο δίκτυο. Στο κεφάλαιο παρέχεται ο ορισμός των γενετικών αλγορίθμων, με περιγραφή των κύριων μερών και μηχανισμών τους, η επεξήγηση των διαφορών τους από τις παραδοσιακές μεθόδους επίλυσης και η ανάλυση των πλεονεκτημάτων χρήσης τους υπό το πρίσμα του εξελικτικού υπολογισμού.
- Το *έκτο* κεφάλαιο επικεντρώνεται στην εφαρμογή του διαμορφωμένου μοντέλου σε επιμέρους μελέτες περιπτώσεων με συνακόλουθη εμπεριστατωμένη παρουσίαση των αποτελεσμάτων. Σε αυτό το πλαίσιο, ως βάση για τη διεξαγωγή μίας σειράς αναλύσεων χρησιμοποιείται ένα δοκιμαστικό δίκτυο. Οι πραγματοποιούμενες αναλύσεις μπορούν να διακριθούν σε τέσσερις κατηγορίες: (α) αναλύσεις που σχετίζονται με αλλαγές στα φυσικά χαρακτηριστικά του δικτύου, συμπεριλαμβανομένων αλλαγών στην τοπολογία αυτού (διακοπή κόμβων και συνδέσμων) και στη χωρητικότητα των συνδέσμων, (β)

αναλύσεις που σχετίζονται με τροποποιήσεις παραμέτρων του προβλήματος, συμπεριλαμβανομένων αλλαγών στις τιμές του παράγοντα ποινής P (που εμπλέκεται στη διαδικασία γένεσης διαδρομών) και του συντελεστή διασποράς θ (που καταδεικνύει την απόκλιση μεταξύ των μετακινούμενων και εμπλέκεται στο μοντέλο της στοχαστικής ισορροπίας του χρήστη), οι οποίες και συμπληρώνονται, στην τελευταία περίπτωση, με αναλύσεις καταμερισμού της κυκλοφορίας στο δίκτυο σύμφωνα με τις αρχές της αιτιοκρατικής ισορροπίας του χρήστη και της βελτιστοποίησης του συστήματος, (γ) αναλύσεις που σχετίζονται με διακυμάνσεις της ζήτησης μεταξύ των ζευγών προέλευσης - προορισμού του δικτύου, και τέλος, (δ) αναλύσεις που σχετίζονται με μεταβολές των συντελεστών βαρύτητας των όρων της αντικειμενικής συνάρτησης του ανώτερου επιπέδου της δι-επίπεδης διατύπωσης του προβλήματος (ανάλυση ευαισθησίας). Σε αυτό το πλαίσιο, ο στόχος των αναλύσεων είναι διττός και μπορεί να συνοψιστεί ως εξής: (α) να εξεταστεί η αποδοτικότητα και η αποτελεσματικότητα του αλγόριθμου στη βελτίωση της απόδοσης του δικτύου, και (β) να διερευνηθεί η υποκείμενη σχέση μεταξύ της βέλτιστης λύσης του προβλήματος και των προαναφερθέντων αλλαγών στις παραμέτρους εισαγωγής. Η επίδειξη των αποτελεσμάτων της ανάλυσης πραγματοποιείται με τη χρήση διαφόρων τύπων πινάκων και διαγραμμάτων (ορισμένα από τα οποία παρατίθενται στο Παράρτημα Γ) τα οποία αφορούν είτε σε επιμέρους μελέτες περιπτώσεων, είτε εστιάζουν στην εκτέλεση συγκριτικών αξιολογήσεων μεταξύ των διακριτών πειραμάτων. Τέλος, πραγματοποιείται επεξήγηση των αποτελεσμάτων και συζήτηση επ' αυτών προκειμένου να δοθεί έμφαση σε συγκεκριμένες διαστάσεις του προβλήματος και να προκύψουν τα συμπεράσματα της ανάλυσης.

- Το *έβδομο* κεφάλαιο συνοψίζει τα ευρήματα της διδακτορικής διατριβής και τη συνεισφορά αυτής στη βιβλιογραφία και εξάγει τα κύρια συμπεράσματα από την έρευνα που πραγματοποιήθηκε. Επιπλέον, στο κεφάλαιο προτείνονται και αναλύονται πιθανές κατευθύνσεις για μελλοντική έρευνα.

Η διδακτορική διατριβή ολοκληρώνεται με τις βιβλιογραφικές αναφορές που παρατίθενται στο κείμενο και τα Παραρτήματα Α, Β και Γ.

ΕΠ.3 Μαθηματική διατύπωση προτεινόμενου μοντέλου

Εξειδικεύοντας τα προαναφερθέντα και εστιάζοντας στη μαθηματική διατύπωση του προβλήματος, αυτή αναλύεται ως εξής: Έστω ότι $G(N,A)$ είναι ένα προσανατολισμένο δίκτυο, όπου N είναι ένα σύνολο κόμβων και A είναι ένα διατεταγμένο σύνολο συνδέσμων. Για κάθε προσανατολισμένο σύνδεσμο (i,j), ορίζεται το μήκος αυτού d_{ij}, ο χρόνος διαδρομής ελεύθερης ροής $t_{f,ij}$, η χωρητικότητά του c_{ij} και ο αρχικός αριθμός λωρίδων κυκλοφορίας που διαθέτει l_{ij}. Επίσης, έστω ότι $N_1 \subseteq N$ είναι ένα υποσύνολο κόμβων που αντιστοιχεί στα κεντροειδή του δικτύου. Για δύο κεντροειδή $(r,s) \in N_1$, η ζήτηση μεταξύ του αντίστοιχου ζεύγους προέλευσης - προορισμού σημειώνεται ως q^{rs} και ο πίνακας ζήτησης μεταξύ όλων των ζευγών ως $OD = \{q^{rs}\}, \forall (r,s) \in N_1$. Σε ό,τι αφορά στον καταμερισμό της κυκλοφορίας, η κυκλοφοριακή ροή και ο χρόνος διαδρομής επί των συνδέσμων ορίζονται ως x_{ij} και t_{ij} αντίστοιχα. Ακόμη, έστω ότι $K_{h,pr}$ είναι το σύνολο των διαδρομών αυξημένης προτεραιότητας που συνδέουν τους κόμβους αυξημένης σπουδαιότητας του υποσυνόλου N_{sp} με συγκεκριμένους κόμβους του υποσυνόλου N_1 και ότι K είναι το σύνολο που περιλαμβάνει όλες τις διαδρομές στο δίκτυο G. Στο μοντέλο, ως d_k^{rs} και t_k^{rs} ορίζονται το μήκος και ο χρόνος διαδρομής της διαδρομής k που συνδέει το ζεύγος προέλευσης - προορισμού (r,s), ενώ w^{rs} είναι η βαρύτητα προορισμού του κόμβου s για τους μετακινούμενους που προέρχονται από τον κόμβο r. Επιπλέον, ορίζεται ο δείκτης $\delta_{ij,k}^{rs} = \{0,1\}$, όπου $\delta_{ij,k}^{rs} = 1$ εάν ο σύνδεσμος (i,j) αποτελεί τμήμα της διαδρομής k που συνδέει το ζεύγος προέλευσης - προορισμού (r,s). Οι εκφράσεις Y και Z αποτελούν τις αντικειμενικές συναρτήσεις του ανώτερου και του κατώτερου επιπέδου αντίστοιχα.

Σε αυτό το πλαίσιο, το πρόβλημα εστιάζει: (α) στην ανακατανομή των λωρίδων κυκλοφορίας κατά μήκος των συνδέσμων του δικτύου, (β) στην αναπροσαρμογή της ζήτησης μεταξύ των ζευγών προέλευσης - προορισμού, και (γ) στην επίτευξη του μέγιστου δυνατού βαθμού προσβασιμότητας μεταξύ του συνόλου των ζευγών προέλευσης - προορισμού του δικτύου, με ιδιαίτερη έμφαση να δίδεται στην πρόσβαση προς τους κόμβους αυξημένης σπουδαιότητας (νοσοκομεία, αστυνομικά τμήματα, πυροσβεστικοί σταθμοί, καταφύγια κλπ). Κατά συνέπεια, ως y_{ij} ορίζεται ο αριθμός των λωρίδων κυκλοφορίας κατά μήκος του προσανατολισμένου συνδέσμου (i,j) μετά το πέρας της διαδικασίας βελτιστοποίησης, και φ^{rs} είναι το ποσοστό αναπροσαρμογής της ζήτησης μεταξύ του ζεύγους προέλευσης - προορισμού (r,s). Τα σύνολα, οι παράμετροι και οι μεταβλητές που χρησιμοποιούνται στο μοντέλο συνοψίζονται στον **Πίνακα ΕΠ.1**.

Πίνακας ΕΠ.1 Σημειογραφία προβλήματος

Σύνολα	
N	σύνολο κόμβων
N_1	σύνολο κεντροειδών
N_{sp}	σύνολο κόμβων αυξημένης σπουδαιότητας
A	σύνολο συνδέσμων
K	σύνολο διαδρομών
$K_{h,pr}$	σύνολο διαδρομών αυξημένης προτεραιότητας
Παράμετροι	
Y	αντικειμενική συνάρτηση ανώτερου επιπέδου
Z	αντικειμενική συνάρτηση κατώτερου επιπέδου
d_{ij}	μήκος συνδέσμου (i,j)
l_{ij}	αρχικός αριθμός λωρίδων κυκλοφορίας επί του συνδέσμου (i,j)
c_{ij}	χωρητικότητα συνδέσμου (i,j)
$t_{f,ij}$	χρόνος διαδρομής ελεύθερης ροής επί του συνδέσμου (i,j)

t_{ij}	χρόνος διαδρομής επί του συνδέσμου (i, j)
x_{ij}	κυκλοφοριακή ροή επί του συνδέσμου (i, j)
q^{rs}	ζήτηση μεταξύ του ζεύγους προέλευσης - προορισμού (ΠΠ) (r,s)
d_k^{rs}	μήκος της διαδρομής k που συνδέει το ζεύγος ΠΠ (r,s)
t_k^{rs}	χρόνος διαδρομής επί της διαδρομής k που συνδέει το ζεύγος ΠΠ (r,s)
$\delta_{ij,k}^{rs}$	δείκτης ότι ο σύνδεσμος (i, j) αποτελεί τμήμα της διαδρομής k που συνδέει το ζεύγος ΠΠ (r,s) $\left(\delta_{ij,k}^{rs} = 0 \text{ ή } 1\right)$
α	συντελεστής βαρύτητας $(0 \le \alpha \le 1)$
w^{rs}	βαρύτητα προορισμού του κόμβου s για τους μετακινούμενους που προέρχονται από τον κόμβο r
m_2, m_3	παράμετροι της συνάρτησης BPR
w_1, w_2, w_3	συντελεστές βαρύτητας
$f_{k(km)}^{rs}$	ροή επί της διαδρομής k του συνόλου διαδρομών (k,m) που συνδέουν το ζεύγος ΠΠ (r,s)
P_k^{rs}	πιθανότητα επιλογής της διαδρομής k που συνδέει το ζεύγος ΠΠ (r,s)
P_{km}^{rs}	οριακή πιθανότητα επιλογής του συνόλου διαδρομών (k,m) που συνδέουν το ζεύγος ΠΠ (r,s)
$P_{k/km}^{rs}$	εξαρτημένη πιθανότητα επιλογής της διαδρομής k, δεδομένου ότι έχει επιλεγεί το σύνολο διαδρομών (k,m) που συνδέουν το ζεύγος ΠΠ (r,s)
V_k^{rs}	αιτιοκρατική συνιστώσα της χρησιμότητας για τη διαδρομή k που συνδέει το ζεύγος ΠΠ (r,s) $\left(V_k^{rs} = -\theta c_k^{rs}\right)$
θ	συντελεστής διασποράς (υποδηλώνει τη διακύμανση μεταξύ των μετακινούμενων)
c_k^{rs}	γενικευμένο κόστος της διαδρομής k που συνδέει το ζεύγος ΠΠ (r,s)
σ_{km}^{rs}	δείκτης ομοιότητας μεταξύ των διαδρομών k και m του συνόλου διαδρομών (k,m) που συνδέουν το ζεύγος ΠΠ (r,s)
d_{km}^{rs}	μήκος του κοινού τμήματος μεταξύ των διαδρομών k και m του συνόλου διαδρομών (k,m) που συνδέουν το ζεύγος ΠΠ (r,s)
Μεταβλητές απόφασης	
y_{ij}	αριθμός λωρίδων κυκλοφορίας επί του συνδέσμου (i, j)
φ^{rs}	ποσοστό αναπροσαρμογής της ζήτησης μεταξύ του ζεύγους ΠΠ (r,s)

Το πρόβλημα βελτιστοποίησης του ανώτερου επιπέδου διαμορφώνεται ως εξής:

$$\min Y = w_1 \sum_{(i,j)\in A} x_{ij} t_{ij} - w_2 \sum_{(r,s)\in N_1} \varphi^{rs} q^{rs} + \\ + w_3 \left[\alpha \sum_{(r,s)\in N_1} \sum_{k\in K} w^{rs} d_k^{rs} + (1-\alpha) \sum_{(r,s)\in N_1} \sum_{k\in K} w^{rs} t_k^{rs} \right] \tag{ΕΠ.1}$$

υποκείμενο στους ακόλουθους περιορισμούς:

$$y_{ij} = \begin{cases} l_{ij} + l_{ji} - y_{ji} \geq 0, if\, \delta_{ij,k}^{rs} = 0, y_{ji} \geq 0 \\ l_{ij} + l_{ji} - y_{ji} \geq 1, if\, \delta_{ij,k}^{rs} = 1, y_{ji} \geq 1 \end{cases}, \forall (i,j) \in A, k \in K_{h,pr}, (r,s) \in N_1 \tag{ΕΠ.2}$$

$$\sum_{j\in N} y_{ij} \geq 1, \forall (i,j) \in A \tag{ΕΠ.3}$$

$$\sum_{j\in N} y_{ji} \geq 1, \forall (j,i) \in A \tag{ΕΠ.4}$$

$$y_{ij} \in Z, \forall (i,j) \in A \tag{ΕΠ.5}$$

$$c_{ij} = c_{ij}\left(y_{ij}\right), \forall (i,j) \in A \tag{ΕΠ.6}$$

$$w^{rs} = \begin{cases} 1, \varepsilon\acute{\alpha}\nu\; s \in N_{sp}, r \in N_1 \\ \dfrac{\varphi^{rs} q^{rs}}{\sum_{\substack{t\neq r \\ (r,t)\in N_1}} \left(\varphi^{rt} q^{rt}\right)}, \sigma\varepsilon\; \delta\iota\alpha\varphi o\rho\varepsilon\tau\iota\kappa\acute{\eta}\; \pi\varepsilon\rho\acute{\iota}\pi\tau\omega\sigma\eta, \forall (r,s) \in N_1 \end{cases} \tag{ΕΠ.7}$$

$$d_k^{rs} = \sum_{\substack{i\neq j \\ (i,j)\in A}} d_{ij} \delta_{ij,k}^{rs}, \forall k \in K, (r,s) \in N_1 \tag{ΕΠ.8}$$

$$t_k^{rs} = \sum_{\substack{i\neq j \\ (i,j)\in A}} t_{ij} \delta_{ij,k}^{rs}, \forall k \in K, (r,s) \in N_1 \tag{ΕΠ.9}$$

$$\delta_{ij,k}^{rs} = \begin{cases} 1, \varepsilon\acute{\alpha}\nu\; o\; \sigma\acute{\upsilon}\nu\delta\varepsilon\sigma\mu o\varsigma\; (i,j)\; \alpha\nu\acute{\eta}\kappa\varepsilon\iota\; \sigma\tau\eta\; \delta\iota\alpha\delta\rho o\mu\acute{\eta}\; k \\ 0, \sigma\varepsilon\; \delta\iota\alpha\varphi o\rho\varepsilon\tau\iota\kappa\acute{\eta}\; \pi\varepsilon\rho\acute{\iota}\pi\tau\omega\sigma\eta \end{cases}, \forall (i,j) \in A, k \in K, (r,s) \in N_1 \tag{ΕΠ.10}$$

Το πρόβλημα του καταμερισμού της κυκλοφορίας στο κατώτερο επίπεδο εκφράζεται ως εξής:

$$\min Z = \sum_{(i,j)\in A} \int_0^{x_{ij}} t_{ij}(w)dw + \frac{1}{\theta} \sum_{(r,s)\in N_1} \sum_{k\in K} \sum_{\substack{m\neq k \\ m\in K}} \left(1-\sigma_{km}^{rs}\right) f_k^{rs} \ln\left(\frac{f_k^{rs}}{1-\sigma_{km}^{rs}}\right) + \\ + \frac{1}{\theta} \sum_{(r,s)\in N_1} \sum_{\substack{k=1 \\ k\in K}}^{n-1} \sum_{\substack{m=k+1 \\ m\in K}}^{n} \sigma_{km}^{rs} \left(f_k^{rs} + f_m^{rs}\right) \ln\left(\frac{f_k^{rs} + f_m^{rs}}{1-\sigma_{km}^{rs}}\right) \tag{ΕΠ.11}$$

υποκείμενο στους ακόλουθους περιορισμούς:

$$\sum_{k\in K} f_k^{rs} = \varphi^{rs} q^{rs}, \forall (r,s) \in N_1 \tag{ΕΠ.12}$$

$$f_k^{rs} = \varphi^{rs} q^{rs} P_k^{rs}, \forall k \in K, (r,s) \in N_1 \tag{ΕΠ.13}$$

$$P_k^{rs} = \sum\nolimits_{\substack{m \neq k \\ m,k \in K}} P_{km}^{rs} P_{k/km}^{rs}, \forall (r,s) \in N_1 \tag{ΕΠ.14}$$

$$P_{km}^{rs} = \frac{\left(1-\sigma_{km}^{rs}\right)\left[\exp\left(\dfrac{V_k^{rs}}{1-\sigma_{km}^{rs}}\right)+\exp\left(\dfrac{V_m^{rs}}{1-\sigma_{km}^{rs}}\right)\right]^{1-\sigma_{km}^{rs}}}{\sum\nolimits_{\substack{l=1 \\ l\in K}}^{n-1}\sum\nolimits_{\substack{p=l+1 \\ p\in K}}^{n}\left(1-\sigma_{lp}^{rs}\right)\left[\exp\left(\dfrac{V_l^{rs}}{1-\sigma_{lp}^{rs}}\right)+\exp\left(\dfrac{V_p^{rs}}{1-\sigma_{lp}^{rs}}\right)\right]^{1-\sigma_{lp}^{rs}}}, \forall k,m \in K, (r,s) \in N_1 \tag{ΕΠ.15}$$

$$P_{k/km}^{rs} = \frac{\exp\left(\dfrac{V_k^{rs}}{1-\sigma_{km}^{rs}}\right)}{\exp\left(\dfrac{V_k^{rs}}{1-\sigma_{km}^{rs}}\right)+\exp\left(\dfrac{V_m^{rs}}{1-\sigma_{km}^{rs}}\right)}, \forall k,m \in K, (r,s) \in N_1 \tag{ΕΠ.16}$$

$$\sigma_{km}^{rs} = \frac{d_{km}^{rs}}{d_k^{rs}+d_m^{rs}-d_{km}^{rs}}, \forall k,m \in K, (r,s) \in N_1 \tag{ΕΠ.17}$$

$$f_k^{rs} \geq 0, \forall k \in K, (r,s) \in N_1 \tag{ΕΠ.18}$$

$$x_{ij} = \sum\nolimits_{(r,s)\in N_1}\sum\nolimits_{k\in K} f_k^{rs}\delta_{ij,k}^{rs}, \forall (i,j) \in A \tag{ΕΠ.19}$$

$$t_{ij} = t_{f,ij}\left(1+m_2\left(\frac{x_{ij}}{c_{ij}}\right)^{m_3}\right), \forall (i,j) \in A \tag{ΕΠ.20}$$

Η εξ. (ΕΠ.1) αντιστοιχεί στην αντικειμενική συνάρτηση του ανώτερου επιπέδου. Αυτή διαμορφώνεται ως το σταθμισμένο άθροισμα τριών όρων: της ελαχιστοποίησης του ολικού χρόνου διαδρομής στο δίκτυο, της μεγιστοποίησης της εξυπηρετούμενης ζήτησης και της μεγιστοποίησης της προσβασιμότητας μεταξύ των ζευγών προέλευσης - προορισμού. Οι τρεις αυτοί δείκτες λειτουργούν ως ένα πολυ-παραγοντικό μέτρο απόδοσης, εστιάζοντας σε διαφορετικές παραμέτρους της λειτουργικότητας του δικτύου. Ειδικότερα, ο ολικός χρόνος διαδρομής στο δίκτυο εξυπηρετεί ως κριτήριο χρόνου καθώς είναι σε θέση να συνυπολογίσει τόσο τη φυσική υποβάθμιση των υποδομών όσο και τις πιθανές μεταβολές των προτύπων μετακίνησης: αποκλίσεις σε οποιονδήποτε από τους δύο παράγοντες θα έχουν ξεκάθαρη επίπτωση στους χρόνους διαδρομής. Επιπλέον, το ποσοστό της εξυπηρετούμενης ζήτησης στο μετα-καταστροφικό περιβάλλον λειτουργεί ως δείκτης του βαθμού ικανοποίησης των μετακινούμενων. Πολλαπλασιαστές της ζήτησης εφαρμόζονται στους κόμβους προέλευσης, οι οποίοι αναπροσαρμόζουν την αρχικώς παραγόμενη ζήτηση σε επίπεδα που εξυπηρετούν καλύτερα το σκοπό της μεγιστοποίησης της απόδοσης του δικτύου, όπως αυτή εκφράζεται μέσω της αντικειμενικής συνάρτησης του ανώτερου επιπέδου. Σε αυτό το πλαίσιο, ορίζονται διαφορετικά ποσοστά αναπροσαρμογής της ζήτησης για κάθε ένα από τα ζεύγη προέλευσης - προορισμού, με στόχο τη μεγιστοποίηση της εξυπηρέτησης των μετακινούμενων σε επίπεδο συστήματος. Τέλος, ο δείκτης προσβασιμότητας αποτελείται από δύο όρους, με τον πρώτο να βασίζεται στην απόσταση και τον δεύτερο στο χρόνο διαδρομής. Αυτή η διττή προσέγγιση στοχεύει, για ακόμη μία φορά, να αποδώσει την επίπτωση μίας καταστροφής στη δομική και λειτουργική υποβάθμιση του δικτύου. Και οι δύο όροι σταθμίζονται από το συντελεστή της εξ. (ΕΠ.7) καθώς και από έναν επιπλέον παράγοντα α, ο οποίος καθορίζει τη σχετική βαρύτητά τους. Σε ό,τι αφορά το πρόσημο του όρου προσβασιμότητας, εφόσον η μεγιστοποίηση αυτής επιτυγχάνεται μέσω της ελαχιστοποίησης της διανυόμενης απόστασης και του χρόνου μετακίνησης επί των διαδρομών που συνδέουν το κάθε ζεύγος προέλευσης - προορισμού, ο αντίστοιχος όρος πρέπει να παράξει ένα ελάχιστο. Η αναπροσαρμογή της επιρροής των τριών συνιστωσών της αντικειμενικής συνάρτησης στην εκτίμηση της απόδοσης του δικτύου επιτυγχάνεται με τη χρήση των συντελεστών βαρύτητας w_1, w_2, w_3.

Η δημιουργία διαδρομών στο μοντέλο ακολουθεί τη μέθοδο της επιβολής ποινής στους συνδέσμους του δικτύου (link penalty approach), με το παραγόμενο σύνολο διαδρομών να διαχωρίζεται σε δύο κατηγορίες: διαδρομές αυξημένης και μειωμένης προτεραιότητας. Η ταξινόμηση των διαδρομών πραγματοποιείται στη βάση της σπουδαιότητας των κόμβων. Πιο συγκεκριμένα, ως διαδρομές αυξημένης προτεραιότητας ορίζονται εκείνες που συνδέουν τους κόμβους αυξημένης σπουδαιότητας του υποσυνόλου N_{sp} με συγκεκριμένους κόμβους του υποσυνόλου N_1, ενώ οι υπόλοιπες διαδρομές που διαμορφώνονται εντάσσονται σε αυτές της μειωμένης προτεραιότητας. Στο μοντέλο, οι κόμβοι αυξημένης σπουδαιότητας αντιστοιχούν σε εγκαταστάσεις οι οποίες είναι ζωτικής σημασίας για την ασφάλεια του πληθυσμού, την αποκατάσταση της κοινωνίας και τη συνέχιση των πάσης φύσεως δραστηριοτήτων όπως νοσοκομεία, αστυνομικά τμήματα, πυροσβεστικοί σταθμοί, καταφύγια κοκ. Εξαιτίας της κρισιμότητας των εγκαταστάσεων αυτών, είναι σημαντικό να δοθεί προσοχή στις διαδρομές που τις εξυπηρετούν σε όρους σύνθεσης και λειτουργικών χαρακτηριστικών. Αυτό πραγματοποιείται με την εξασφάλιση, στο μέγιστο δυνατό βαθμό, υψηλής προσβασιμότητας προς αυτές τις εγκαταστάσεις ενώ η αναδιάταξη των λωρίδων κυκλοφορίας γίνεται με τρόπο που να εξασφαλίζει τη δυνατότητα κίνησης και προς τις δύο κατευθύνσεις. Οι σύνδεσμοι που διαμορφώνουν τις διαδρομές μπορεί να ανήκουν και στα δύο είδη που τις απαρτίζουν, καθώς οι διαδρομές αυξημένης και μειωμένης προτεραιότητας δεν είναι απαραίτητο να διαχωρίζονται μεταξύ τους. Σε αυτό το πλαίσιο, η εξ. (ΕΠ.2) καθορίζει τον αριθμό των λωρίδων κυκλοφορίας ανά σύνδεσμο. Ωστόσο, στην περίπτωση συνδέσμων που αποτελούν τμήμα διαδρομών αυξημένης προτεραιότητας, η εξ. (ΕΠ.2) αποκλείει την πιθανότητα ολικής αναστροφής της κυκλοφορίας με την εξασφάλιση της ύπαρξης τουλάχιστον μίας λωρίδας κυκλοφορίας ανά κατεύθυνση. Επιπλέον, οι εξ. (ΕΠ.3) και (ΕΠ.4) επιτυγχάνουν την ύπαρξη τουλάχιστον μίας λωρίδας κυκλοφορίας με κατεύθυνση από ή προς κάθε κόμβο του δικτύου αντίστοιχα, τονίζοντας με αυτόν τον τρόπο την ανάγκη να διατηρηθεί η συνδεσιμότητα του τελευταίου. Η εξ. (ΕΠ.5) περιορίζει τη μεταβλητή απόφασης στη λήψη μόνο ακέραιων τιμών. Η εξ. (ΕΠ.6) ορίζει τη χωρητικότητα των συνδέσμων. Η εξ. (ΕΠ.7) υπολογίζει το συντελεστή βαρύτητας για κάθε κόμβο προορισμού στη βάση τόσο της σπουδαιότητας αυτού, όσο και της υπάρχουσας ζήτησης στον κόμβο προέλευσης. Η εξ. (ΕΠ.8) υπολογίζει τα μήκη των διαδρομών, ενώ η εξ. (ΕΠ.9) εκτιμά τους αντίστοιχους χρόνους διαδρομής. Η εξ. (ΕΠ.10) αποτελεί δείκτη του εάν κάποιος σύνδεσμος αποτελεί τμήμα κάποιας διαδρομής.

Η εξ. (ΕΠ.11) αντιστοιχεί στην αντικειμενική συνάρτηση του κατώτερου επιπέδου και πραγματοποιεί τον καταμερισμό της κυκλοφορίας στο δίκτυο, αποτελώντας τη διατύπωση του μοντέλου paired combinatorial logit (PCL). Η εξ. (ΕΠ.12) περιορίζει το άθροισμα των ροών επί των διαδρομών που συνδέουν ένα ζεύγος προέλευσης - προορισμού να είναι αντίστοιχο της ζήτησης που δημιουργείται μεταξύ αυτού του ζεύγους. Η εξ. (ΕΠ.13) ορίζει τη ροή επί μίας διαδρομής μεταξύ ενός ζεύγους προέλευσης - προορισμού να είναι ανάλογη τόσο της υπάρχουσας ζήτησης μεταξύ αυτού του ζεύγους, όσο και της πιθανότητας να επιλεγεί αυτή η διαδρομή. Όπως υποδηλώνεται από την εξ. (ΕΠ.14), στο μοντέλο PCL, η πιθανότητα να επιλεγεί η διαδρομή k από το σύνολο διαδρομών (k,m) που συνδέουν το ζεύγος προέλευσης - προορισμού (r,s) βασίζεται: (α) στην οριακή πιθανότητα να επιλεγεί το ζεύγος (k,m) από το σύνολο των διαδρομών που συνδέουν το ζεύγος προέλευσης - προορισμού (r,s) (εξ. (ΕΠ.15)) και, (β) στην εξαρτημένη πιθανότητα να επιλεγεί η διαδρομή k, δεδομένου ότι έχει ήδη επιλεγεί το ζεύγος (k,m) (εξ. (ΕΠ.16)). Η εξ. (ΕΠ.17) αποτελεί ένα μέτρο ομοιότητας μεταξύ των διαδρομών που συνθέτουν το κάθε ζεύγος. Η εξ. (ΕΠ.18) περιορίζει τις ροές επί των διαδρομών να παίρνουν θετικές τιμές, ενώ η εξ. (ΕΠ.19) υπολογίζει τη ροή σε κάθε σύνδεσμο του δικτύου. Τέλος, η εξ. (ΕΠ.20) είναι η συνάρτηση του Bureau of Public Roads (BPR).

Ωστόσο, οι τρεις συνιστώσες της αντικειμενικής συνάρτησης διακρίνονται από διαφορετικές μονάδες μέτρησης και τάξεις μεγέθους. Κατά συνέπεια, οι όροι μετατρέπονται στις αδιάστατες, κανονικοποιημένες μορφές τους σύμφωνα με τον τύπο (Proos et al., 2001):

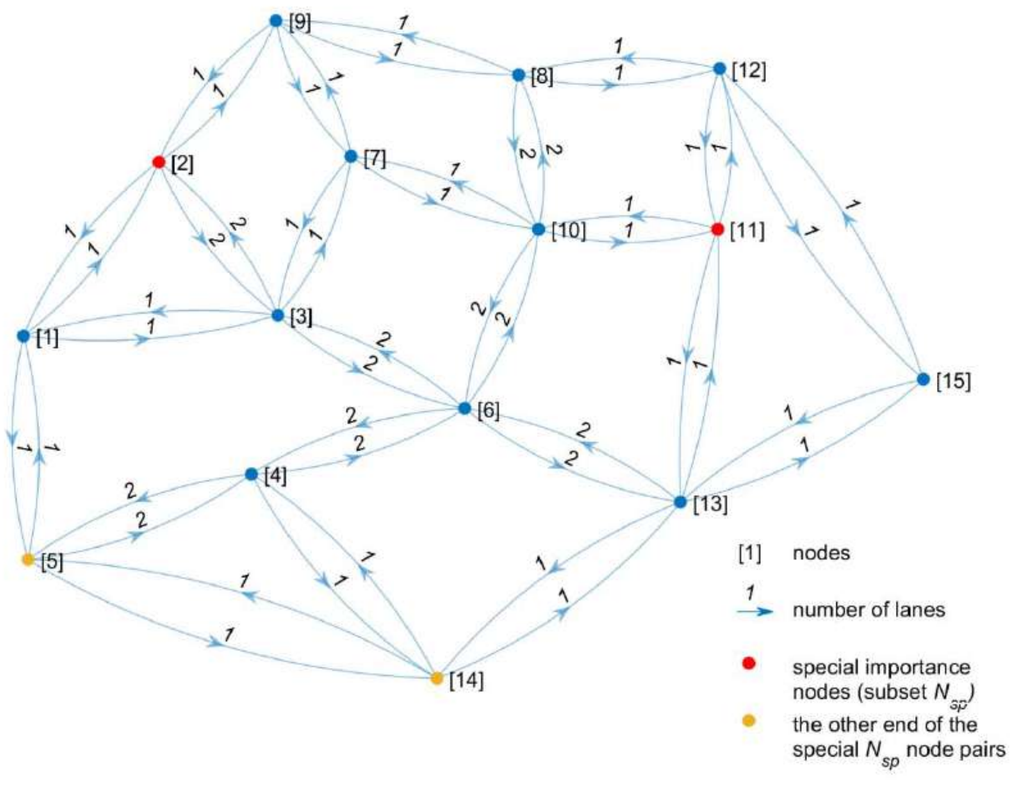
$$Z_{k,norm} = \frac{Z_k}{\left|Z_{k,\max}\right|} \tag{ΕΠ.21}$$

όπου $Z_{k,norm}$ είναι η κανονικοποιημένη τιμή της συνιστώσας Z_k η οποία βρίσκεται εντός του διαστήματος $[0,1]$, και $\left|Z_{k,\max}\right|$ είναι η μέγιστη πιθανή τιμή του Z_k χωρίς παραβίαση των περιορισμών. Οι μέγιστες τιμές για τον ολικό χρόνο διαδρομής στο δίκτυο και την προσβασιμότητα μεταξύ των ζευγών προέλευσης - προορισμού εξάγονται από τους αντίστοιχους υπολογισμούς στο μη βελτιστοποιημένο, μετα-καταστροφικό δίκτυο καθώς αυτές θα υπερέχουν, σε κάθε περίπτωση, εκείνων που προκύπτουν μετά τη διαδικασία βελτιστοποίησης. Σε ό,τι αφορά τη μέγιστη τιμή της εξυπηρετούμενης ζήτησης, αυτή ισούται με την αρχική, μη αναπροσαρμοσμένη ολική ζήτηση στο δίκτυο. Αυτό οφείλεται στη φύση της στρατηγικής ρύθμισης της ζήτησης σύμφωνα με την οποία, οποιαδήποτε τιμή της εξυπηρετούμενης ζήτησης εξάγεται στο βελτιστοποιημένο δίκτυο θα είναι οπωσδήποτε μικρότερη ή το πολύ ίση της αντίστοιχης τιμής που διαμορφώθηκε αμέσως μετά το πέρας της καταστροφής.

ΕΠ.4 Αναλύσεις

Προκειμένου να ελεγχθεί, και εν τέλει να αποτυπωθεί, η ικανότητα του προτεινόμενου μοντέλου σε όρους βελτίωσης της λειτουργικότητας του δικτύου μετά από καταστροφικό γεγονός, το μεθοδολογικό πλαίσιο εφαρμόζεται σε ένα δοκιμαστικό δίκτυο με δεκαπέντε κόμβους και σαράντα οκτώ συνδέσμους. Η διάταξη του δικτύου παρουσιάζεται στην **Εικόνα ΕΠ.1**. Σε αυτό το δίκτυο, οι κόμβοι *2* και *11* θεωρούνται κόμβοι αυξημένης σπουδαιότητας (υποσύνολο N_{sp}): υπενθυμίζεται ότι αυτοί αντιστοιχούν σε εγκαταστάσεις οι οποίες είναι ζωτικής σημασίας για την ασφάλεια του πληθυσμού, την αποκατάσταση της κοινωνίας και τη συνέχιση των δραστηριοτήτων (για παράδειγμα, ο κόμβος *2* θα μπορούσε να αντιστοιχεί στο νοσοκομείο της πόλης και ο κόμβος *11* στο αστυνομικό τμήμα). Οι κόμβοι *5* και *14* αποτελούν το άλλο άκρο των ζευγών κόμβων που δημιουργούνται με το υποσύνολο N_{sp}, μεταξύ των οποίων σχηματίζονται οι διαδρομές αυξημένης σπουδαιότητας. Κατά συνέπεια, οι διαδρομές που εξυπηρετούν τα ζεύγη κόμβων $(2-5)$, $(5-2)$, $(2-14)$, $(14-2)$, $(11-5)$, $(5-11)$, $(11-14)$ και $(14-11)$ εξαιρούνται από την πιθανότητα ολικής αναστροφής της κυκλοφορίας στα επιμέρους τμήματά τους και θα πρέπει να εξασφαλίζεται η ύπαρξη τουλάχιστον μίας λωρίδας ανά κατεύθυνση αντίστοιχα. Οι διαδρομές που συνδέουν τα υπόλοιπα ζεύγη προέλευσης - προορισμού (διαδρομές μειωμένης σπουδαιότητας) δεν υπόκεινται σε τέτοιου τύπου περιορισμούς, με αποτέλεσμα να είναι δυνατή η ολική αναστροφή της κυκλοφορίας ανά τμήμα.

Σε ό,τι αφορά την αρχική, μη αναπροσαρμοσμένη ζήτηση μεταξύ των ζευγών προέλευσης - προορισμού (η οποία διατηρείται σταθερή μεταξύ των περισσοτέρων αναλύσεων), αυτή δημιουργείται τυχαία σύμφωνα με την κανονική κατανομή, με τις προκύπτουσες τιμές του q^{rs} να υπόκεινται σε ανώτερα και κατώτερα πιθανά όρια τιμών.



Εικόνα ΕΠ.1 Διαμόρφωση δοκιμαστικού δικτύου *15* κόμβων

Οι αναλύσεις επί του δοκιμαστικού δικτύου βασίζονται στη διαμόρφωση σεναρίων τα οποία μελετούν τον τρόπο με τον οποίο διαφοροποιήσεις των επιμέρους παραμέτρων του προβλήματος επηρεάζουν το αναμενόμενο αποτέλεσμα. Τριάντα αναλύσεις εκτελούνται ανά περίπτωση για κάθε έναν από τους έξι συνδυασμούς των παραμέτρων διασταύρωσης και μετάλλαξης του γενετικού αλγόριθμου. Το αποτέλεσμα είναι ένα σύνολο εκατόν ογδόντα αναλύσεων για κάθε ένα από τα σενάρια που αφορούν σε αλλαγές: (α) στα φυσικά χαρακτηριστικά του δικτύου, (β) στις παραμέτρους P και θ, και (γ) στη γενόμενη ζήτηση. Το ίδιο αφορά και στις αναλύσεις που πραγματοποιούν αιτιοκρατικό καταμερισμό της κυκλοφορίας στο δίκτυο σύμφωνα με τα μοντέλα deterministic user equilibrium (DUE) και system optimum (SO). Τέλος, σε ό,τι αφορά τις αναλύσεις ευαισθησίας, αυτές επίσης αγγίζουν τον αριθμό των εκατόν ογδόντα, με τριάντα αναλύσεις να πραγματοποιούνται για κάθε έναν από τους έξι συνδυασμούς των συντελεστών βαρύτητας των όρων της αντικειμενικής συνάρτησης του ανώτερου επιπέδου. Το αποτέλεσμα είναι η διενέργεια στο σύνολο 1620 αναλύσεων. Ο **Πίνακας ΕΠ.2** συνοψίζει τα σενάρια που εξετάστηκαν ανά παράμετρο διαφοροποίησης ενώ αναφέρει και τους πίνακες όπου παρατίθενται τα αποτελέσματα των αναλύσεων.

Πίνακας ΕΠ.2 Σενάρια που εξετάστηκαν

Παράμετρος	Σενάριο
Φυσικά χαρακτηριστικά του δικτύου (μερικές ή ολικές βλάβες στοιχείων του δικτύου)	Σενάριο βάσης (δίκτυο *15* κόμβων με c_{ij} = 900 οχήματα/ώρα/λωρίδα) (**Table 6.4**)
	Σενάριο μείωσης της χωρητικότητας των συνδέσμων (δίκτυο *15* κόμβων με c_{ij} = 500 οχήματα/ώρα/λωρίδα) (**Table C.1**)
	Σενάριο ολικής βλάβης στοιχείου του δικτύου (δίκτυο *14* κόμβων με c_{ij} = 900 οχήματα/ώρα/λωρίδα) (**Table C.2**)
Παράμετροι του προβλήματος (διακύμανση μεταξύ των μετακινούμενων και διαδικασία δημιουργίας διαδρομών)	Σενάριο αυξημένου επιπέδου στοχαστικότητας (δίκτυο *15* κόμβων με c_{ij} = 900 οχήματα/ώρα/λωρίδα και θ = 0.01) (**Table C.3**)
	Ανάλυση DUE (δίκτυο *15* κόμβων με c_{ij} = 900 οχήματα/ώρα/λωρίδα) (**Table C.4**)
	Ανάλυση SO (δίκτυο *15* κόμβων με c_{ij} = 900 οχήματα/ώρα/λωρίδα) (**Table C.5**)
	Σενάριο αυξημένης ανομοιότητας μεταξύ των διαδρομών (δίκτυο *15* κόμβων με c_{ij} = 900 οχήματα/ώρα/λωρίδα και P = 0.5) (**Table C.6**)
Ζήτηση	Σενάριο αύξησης της ζήτησης (δίκτυο *15* κόμβων με c_{ij} = 900 οχήματα/ώρα/λωρίδα και $q^{rs'} = 2.0q^{rs}$) (**Table C.7**)
Ανάλυση ευαισθησίας	Έξι συνδυασμοί των συντελεστών βαρύτητας (w_1, w_2, w_3) (δίκτυο *15* κόμβων με c_{ij} = 900 οχήματα/ώρα/λωρίδα) (**Table 6.12**)

ΕΠ.5 Συμπεράσματα

Τα κύρια συμπεράσματα που προέκυψαν από τις αναλύσεις που πραγματοποιήθηκαν μπορούν να συνοψισθούν ως εξής:

- Ανεξάρτητα από την ανάλυση που κάθε φορά εξετάζεται, ο χώρος των λύσεων παρουσιάζει μία λίγο - πολύ σταθερή μορφή, καθώς, σε γενικές γραμμές, τα βέλτιστα αποτελέσματα συγκεντρώνονται σε δύο σετ λύσεων. Περαιτέρω ανάλυση αυτού του σχηματισμού υποδεικνύει ότι τα σετ αυτά αντιστοιχούν σε λύσεις διακριτής ποιότητας, με την πρώτη ομάδα να παρουσιάζει συστηματικά βελτιωμένη απόδοση σε κάθε έναν από τους επιμέρους δείκτες της αντικειμενικής συνάρτησης. Η συγκριτικά καλύτερη αυτή απόδοση εξασφαλίζεται μέσω μικρότερου ολικού χρόνου διαδρομής στο δίκτυο, χαμηλότερων τιμών στους δείκτες προσβασιμότητας με βάση την απόσταση και το χρόνο διαδρομής (γεγονός που υποδηλώνει βελτιωμένες συνθήκες προσβασιμότητας) και υψηλότερων ποσοστών εξυπηρετούμενης ζήτησης. Ως εκ τούτου, είναι αναμενόμενο ότι τα καλύτερα πειράματα όλων των συνδυασμών μεταξύ των ποσοστών διασταύρωσης και μετάλλαξης ανήκουν σε αυτή την ομάδα. Η απόκλιση σε όρους απόδοσης μεταξύ των δύο σετ λύσεων μπορεί να αποδοθεί στην καλύτερη αξιοποίηση και των δύο στρατηγικών διαχείρισης από την πρώτη ομάδα. Αυτό υποδεικνύεται τόσο από τη μεγαλύτερη συχνότητα εναλλαγής λωρίδων μεταξύ των συνδέσμων του δικτύου, όσο και από τα αυξημένα ποσοστά εξυπηρετούμενης ζήτησης που επιτυγχάνονται από το πρώτο σετ λύσεων.

- Σε γενικές γραμμές, το προτεινόμενο μοντέλο παρουσιάζει μεγαλύτερη ευαισθησία στη διάσταση του χρόνου (ολικός χρόνος διαδρομής στο δίκτυο και δείκτης προσβασιμότητας με βάση το χρόνο διαδρομής) σε σχέση με την παράμετρο της εξυπηρετούμενης ζήτησης ή το μήκος των δημιουργούμενων διαδρομών (δείκτης προσβασιμότητας με βάση την απόσταση). Οι τελευταίοι δύο δείκτες παραμένουν σχετικά σταθεροί σε όλες τις αναλύσεις που πραγματοποιήθηκαν ανά περίπτωση.
- Τα αποτελέσματα της ανάλυσης ευαισθησίας τονίζουν τη σημασία των όρων της εξυπηρετούμενης ζήτησης και της προσβασιμότητας με βάση την απόσταση στην τελική τιμή της αντικειμενικής συνάρτησης. Συγκεκριμένα, όταν λαμβάνονται υπ' όψιν διαφοροποιήσεις των συντελεστών βαρύτητας των επιμέρους όρων στην ανάλυση, οι, κατ' απόλυτο τιμή, μεγαλύτερες τιμές των προαναφερθέντων δεικτών φαίνεται ότι έχουν καθοριστικό ρόλο στο τελικό αποτέλεσμα, αφού οι πολύ μικρές τιμές των δεικτών του χρόνου διαδρομής δεν μπορούν να αντισταθμίσουν την αύξηση ή / και τη μείωση των άλλων δύο στοιχείων ώστε τελικά να επηρεάσουν την τελική τιμή της αντικειμενικής συνάρτησης.
- Στις περισσότερες από τις περιπτώσεις που μελετήθηκαν, η σύγκλιση του αλγόριθμου πραγματοποιείται σχετικά γρήγορα (κατά προσέγγιση μεταξύ της 20^{ης} και της 30^{ης} γενιάς), υποδεικνύοντας ότι μία ικανοποιητική λύση στο πρόβλημα μπορεί να βρεθεί μέσα σε περίπου 55 - 85 λεπτά (επεξεργαστής Intel (R) Core (TM) i7 - 6700 CPU (3.40GHz) με 16GB RAM). Κατά συνέπεια, τα κριτήρια τερματισμού που σχετίζονται με των αριθμό των γενεών που σχηματίστηκαν και τον υπολογιστικό χρόνο που διεκπεραιώθηκε θα μπορούσαν κατ' αντιστοιχία να χαλαρώσουν.
- Δεν είναι δυνατόν να εντοπιστεί ένας κοινός βέλτιστος συνδυασμός των ποσοστών διασταύρωσης και μετάλλαξης για όλα τα σενάρια που εξετάστηκαν, καθώς στις περισσότερες περιπτώσεις τα απολύτως βέλτιστα πειράματα αντιστοιχούν σε διαφορετικούς συνδυασμούς. Παρ' όλ' αυτά, τα ποσοστά διασταύρωσης: 0.90 και μετάλλαξης: 0.05 φαίνεται να παρουσιάζουν ελαφρώς βελτιωμένη απόδοση σε σχέση με τα υπόλοιπα που μελετήθηκαν, χωρίς αυτό, ωστόσο, να συμβαίνει απαραίτητα όταν βρίσκονται σε συνδυασμό μεταξύ τους.
- Όπως ήταν αναμενόμενο, αποδεικνύεται ότι πιθανές αλλαγές στις παραμέτρους της προσφοράς και της ζήτησης στην περίοδο που έπεται ενός καταστροφικού γεγονότος έχουν ξεκάθαρη επίδραση στην απόδοση του δικτύου. Συγκεκριμένα, τόσο οι ολικές (απομάκρυνση συνδέσμων ή / και κόμβων), όσο και οι μερικές (περιορισμοί στη χωρητικότητα των συνδέσμων) βλάβες στα στοιχεία του δικτύου μπορούν να προκαλέσουν σημαντική μείωση της λειτουργικότητάς του, ενώ το ίδιο ισχύει και για τα αυξημένα ποσοστά ζήτησης. Το προτεινόμενο μοντέλο, μολονότι δεν είναι σε θέση να

αντισταθμίσει πλήρως την αρχική υποβάθμιση των λειτουργικών χαρακτηριστικών του δικτύου προκειμένου αυτά να φτάσουν στα επίπεδα του αρχικού σεναρίου, αποδεικνύεται ιδιαιτέρως αποτελεσματικό στη βελτίωση της απόδοσης σε όλες τις περιπτώσεις που εξετάστηκαν.

- Οι αναλύσεις επίσης υποδεικνύουν ότι οι αλλαγές στα λειτουργικά χαρακτηριστικά του δικτύου (μείωση στις παραμέτρους προσφοράς ή / και αύξηση της ζήτησης) περιορίζουν τον διαθέσιμο χώρο των λύσεων, οδηγώντας σε αποτελέσματα με μικρότερες τιμές απόκλισης.
- Αποδεικνύεται πως η διαδικασία του καταμερισμού της κυκλοφορίας στο δίκτυο έχει σημαντική επίπτωση στο τελικό αποτέλεσμα. Συγκεκριμένα, η ενσωμάτωση στοχαστικοτήτων στη διαδικασία επιλογής διαδρομής τείνει να οδηγήσει στην εξαγωγή αποτελεσμάτων που είναι υποδεέστερα αυτών που λαμβάνονται από την εφαρμογή αιτιοκρατικών αρχών. Ως εκ τούτου, τα στοχαστικά μοντέλα δεν φαίνονται, εκ πρώτης όψεως, να είναι εξίσου αποτελεσματικά με τα αιτιοκρατικά ισοδύναμά τους στη βελτίωση της απόδοσης του δικτύου. Ωστόσο, η σχετική βελτίωση που προκύπτει μέσω της εφαρμογής των αρχών της αιτιοκρατικής ισορροπίας του χρήστη (deterministic user equilibrium (DUE)) και του βέλτιστου για το σύστημα (system optimum (SO)) είναι μόνο θεωρητική, καθώς τα μοντέλα αυτά είναι γνωστό πως δεν πληρούν τους όρους καταλληλότητας για την απεικόνιση των μηχανισμών επιλογής διαδρομής υπό συνθήκες έκτακτης ανάγκης. Υπό αυτή την έννοια, τα αποτελέσματα των αναλύσεων όπου γίνεται εφαρμογή του στοχαστικού καταμερισμού της κυκλοφορίας είναι αντίστοιχα της ενσωμάτωσης ενός μεγαλύτερου βαθμού ρεαλισμού στην όλη διαδικασία. Το τελευταίο έρχεται σε αντίθεση με τη συστηματική υπερεκτίμηση της απόδοσης του δικτύου κατά τη χρήση αιτιοκρατικών αρχών επιλογής διαδρομής.
- Σε ό,τι αφορά τη διαδικασία δημιουργίας διαδρομών, τα αποτελέσματα υποδεικνύουν ότι η μείωση του βαθμού ομοιότητας μεταξύ των διαδρομών δεν συνεπάγεται απαραίτητα και βελτίωση της απόδοσης του δικτύου. Πράγματι, μολονότι βελτιωμένες τιμές της αντικειμενικής συνάρτησης (ή / και των επιμέρους δεικτών αυτής) μπορεί περιστασιακά να προκύψουν, δεν είναι δυνατόν να γίνει γενίκευση των μεμονωμένων αυτών αποτελεσμάτων ώστε να μπορεί να υποστηριχθεί η επιλογή της εφαρμογής υψηλότερης ποινής (penalty) κατά τη δημιουργία των διαδρομών. Το γεγονός αυτό μπορεί να αποδοθεί στην αυξημένη απόκλιση των αποτελεσμάτων που παρατηρείται σε αυτές τις περιπτώσεις, και η οποία οδηγεί σε μέτρια συνολική απόδοση και κατά συνέπεια σε προβληματισμό αναφορικά με την προστιθέμενη αξία που προκύπτει από την ανάλυση.
- Ο προτεινόμενος αλγόριθμος απέδειξε ότι παρουσιάζει σταθερή απόδοση και παράγει συνεπή αποτελέσματα σε όλες τις αναλύσεις που πραγματοποιήθηκαν. Το συμπέρασμα αυτό προκύπτει από τον υπολογισμό των συντελεστών διακύμανσης σε όρους μέσης τιμής της αντικειμενικής συνάρτησης για κάθε σενάριο που εξετάστηκε. Πρέπει να τονιστεί πως οι συντελεστές διακύμανσης που προέκυψαν δεν είναι δυνατόν (ούτε θα έπρεπε να αναμένεται) να είναι ιδιαιτέρως χαμηλοί. Αυτό οφείλεται στο γεγονός πως ο αλγόριθμος κάθε φορά εφαρμόζεται σε ένα δίκτυο διαφορετικής διαμόρφωσης (λόγω της

στρατηγικής της αναστροφής των λωρίδων κυκλοφορίας), ενώ παράλληλα υιοθετούνται διακριτά ποσοστά ρύθμισης της ζήτησης μεταξύ των ζευγών προέλευσης - προορισμού. Το γεγονός αυτό επίσης επεξηγεί τη δυσκολία του προτεινόμενου αλγόριθμου να καταλήξει σε μία μοναδική λύση, επιτυγχάνοντας με αυτόν τον τρόπο ακόμα μικρότερες τιμές διακύμανσης στα αποτελέσματα της αντικειμενικής συνάρτησης.

ΕΠ.6 Περιορισμοί

Η εφαρμογή οποιασδήποτε από τις δύο στρατηγικές διαχείρισης (αντιστροφή των λωρίδων κυκλοφορίας ή / και διαχείριση της ζήτησης) αποτελεί αντικείμενο ιδιαίτερου ενδιαφέροντος καθώς οι δυσκολίες που παρουσιάζονται σε μία τέτοια περίπτωση και οι επιπτώσεις τους μπορεί να είναι σημαντικές. Συγκεκριμένα, η αντιστροφή των λωρίδων κυκλοφορίας, μολονότι ιδιαιτέρως αποτελεσματική στη μείωση των χρόνων διαδρομής στο δίκτυο, συνεπάγεται εγγενώς μία αλλαγή στη διάταξη του αυτού. Η αλλαγή αυτή, ωστόσο, λόγω του βραχυπρόθεσμου και επείγοντος χαρακτήρα της, αντίκειται σε οποιαδήποτε προϋπάρχουσα αντίληψη των μετακινούμενων σε σχέση με τη δομή του δικτύου και τα αντίστοιχα κόστη. Κατά συνέπεια καταδεικνύεται η ανεπάρκεια της αρχής της αιτιοκρατικής ισορροπίας του χρήστη σε ό,τι αφορά τον καταμερισμό της κυκλοφορίας στο δίκτυο καθώς και η ανάγκη να περιοριστεί η εκτεταμένη χρήση της. Ακόμη, προκειμένου να εξασφαλιστεί η συστηματική της εφαρμογή, η αντιστροφή των λωρίδων απαιτεί τη διάθεση σημαντικού αριθμού πόρων (οικονομικών ή / και ανθρώπινων) καθώς και χρόνου για να υλοποιηθεί στο δίκτυο, πέραν της ανάγκης για μία ξεκάθαρη και ισχυρή οργανωτική δομή η οποία θα επιτρέπει, θα εδραιώνει και θα προωθεί την επικοινωνία, το συντονισμό και τη συνεργασία μεταξύ των εμπλεκόμενων φορέων. Υπό αυτή την έννοια, η αντιστροφή των λωρίδων φαίνεται ότι είναι ευκολότερα εφαρμόσιμη σε δρόμους, τα λειτουργικά χαρακτηριστικά των οποίων είναι τέτοια, ώστε τα αναμενόμενα οφέλη από την εφαρμογή της να υπερτερούν του αντίστοιχου κόστους (π.χ. αρτηρίες με πολλαπλές λωρίδες ανά κατεύθυνση και αυξημένα όρια ταχύτητας). Επιπλέον, εξαιτίας των δυσκολιών που παρουσιάζονται, η αντιστροφή των λωρίδων κυκλοφορίας δεν μπορεί, σε γενικές γραμμές, να αποτελεί μία αυθόρμητη απόφαση από πλευράς των αρχών, καταδεικνύοντας την ανάγκη κατάστρωσης σε πρότερο χρόνο στρατηγικών σχεδίων εφαρμογής στη βάση διαφορετικών σεναρίων.

Από την άλλη πλευρά, η διαχείριση της ζήτησης μπορεί να αποδειχτεί ακόμη δυσκολότερη. Η πιθανότητα παρέμβασης στο πρώτο βήμα του σχεδιασμού των μεταφορών, αν και πολλά υποσχόμενη, είναι εν τέλει δύσκολο να επιτευχθεί. Φαίνεται πως η διαχείριση της ζήτησης θα απαιτούσε ένα τρόπο επικοινωνίας με τους δυνητικούς χρήστες του δικτύου καθώς και επαρκή ποσοστά συμμόρφωσης από μέρους τους. Ωστόσο, θα απαιτούσε και έναν πιθανό τρόπο επιβολής της συμμόρφωσης σε περίπτωση που αυτή δεν επιτυγχανόταν σε επαρκή ποσοστά σε καθαρά εθελοντική βάση. Παρότι η επικοινωνία των οδηγιών προς τους μετακινούμενους θα μπορούσε να πραγματοποιηθεί με διάφορους τρόπους στην περίπτωση της ολικής απαγόρευσης μετακινήσεων, η διαδικασία περιπλέκεται στην περίπτωση της μερικής απαγόρευσης (όπως στην περίπτωση που εξετάζεται), όπου οι δυνητικοί χρήστες του δικτύου θα πρέπει πρώτα να ενημερωθούν για το εάν επιτρέπεται να μετακινηθούν. Κατά συνέπεια, η επικοινωνία στη δεύτερη περίπτωση είναι αναγκαίο να λάβει μία πιο εξατομικευμένη μορφή, η οποία προβλέπεται ότι θα καταστεί δυνατή στο μέλλον μέσω των τεχνολογικών εξελίξεων. Επιπλέον, η συμμόρφωση των μετακινούμενων προς τις οδηγίες αποτελεί και αυτή αντικείμενο συζήτησης καθώς οι έως τώρα μελέτες σε ό,τι αφορά τους υποκείμενους συμπεριφορικούς μηχανισμούς οι οποίοι διαμορφώνουν τις αντιδράσεις των ατόμων υπό συνθήκες έκτακτης ανάγκης είναι μάλλον ποιοτικές, ενώ τα αποτελέσματα από τη συγκριτική τους αξιολόγηση δεν έχουν καταλήξει σε σαφή συμπεράσματα. Κατά συνέπεια, η συμμόρφωση των χρηστών δεν θα πρέπει να θεωρείται δεδομένη, τονίζοντας με αυτόν τον τρόπο την ανάγκη να θεσπιστούν πιθανοί μηχανισμοί επιβολής. Υπό αυτή την έννοια, δεν προκαλεί έκπληξη το γεγονός ότι οι δυσκολίες που σχετίζονται με την εφαρμογή της στρατηγικής διαχείρισης της ζήτησης την έχουν περιορίσει, προς το παρόν, σε ένα μάλλον θεωρητικό πλαίσιο παρά σε ένα πρακτικά εφαρμόσιμο.

Σε ό,τι αφορά τον αλγόριθμο δημιουργίας διαδρομών, θα πρέπει να τονιστεί ότι ο σχηματισμός (επαρκώς) ανομοιόμορφων διαδρομών εξαρτάται από τις εκάστοτε διαθέσιμες εναλλακτικές. Αυτές υλοποιούνται μέσω των όσων ορίζει το πρόβλημα του ανώτερου επιπέδου σε σχέση με την αντιστροφή των λωρίδων κυκλοφορίας και την προκύπτουσα μορφή του δικτύου. Υπό αυτή τη έννοια, η δομή του δικτύου μπορεί να παρουσιάζει μεγαλύτερες δυσκολίες στην περίπτωση της πλήρους αναστροφής των λωρίδων κυκλοφορίας, όπου ορισμένοι σύνδεσμοι διπλής κατεύθυνσης μπορεί, μετά την ανακατανομή των λωρίδων, να γίνουν μονής. Επιπλέον, η υπάρχουσα συνάρτηση κόστους μεταξύ των συνδέσμων που συντρέχουν σε έναν κόμβο μπορεί να έχει καταλυτική επίδραση στη δημιουργία ανομοιόμορφων διαδρομών. Πράγματι, στην περίπτωση δύο συνδέσμων που ξεκινούν από τον ίδιο κόμβο, μία σημαντική διαφορά στο μεταξύ τους κόστος θα μπορούσε να οδηγήσει την τιμή του παράγοντα ποινής σε υπέρμετρη αύξηση προκειμένου να προκύψει μία διαφορετική διαδρομή. Ωστόσο, η χρήση υψηλών τιμών ποινής μπορεί να προκαλέσει το σχηματισμό απαγορευτικών, από άποψη κόστους, διαδρομών οι οποίες θα ήταν μη ελκυστικές προς τους χρήστες. Κατά συνέπεια, η κρισιμότητα του παράγοντα ποινής υποδηλώνει ότι αυτός θα πρέπει να εξυπηρετεί δύο διαφορετικούς στόχους: από τη μία να προωθεί τη διαφορετικότητα του συνόλου των δημιουργούμενων διαδρομών, ενώ από την άλλη να διασφαλίζει ότι οι συγκεκριμένες διαδρομές είναι λογικές από την πλευρά του χρήστη. Τέλος, η επαναληπτική δημιουργία των διαδρομών αυξάνει την υπολογιστική πολυπλοκότητα του μοντέλου. Συγκεκριμένα, από τη στιγμή που κάθε ένα από τα άτομα που συνιστούν τον πληθυσμό αποτελεί μία πιθανή λύση στο πρόβλημα με μία αντίστοιχη διαμόρφωση δικτύου, ο αλγόριθμος δημιουργίας των διαδρομών εκτελείται για κάθε ένα από αυτά τα δίκτυα σε αναζήτηση των αντίστοιχων συντομότερων διαδρομών. Η δημιουργία διαδρομών με αυτόν τον τρόπο μπορεί να είναι ιδιαιτέρως επίπονη σε περιπτώσεις όπου η τιμή του παράγοντα ποινής τίθεται ψηλά, το βήμα της ποινής παραμένει σχετικά μικρό και ο αλγόριθμος πρέπει να επαναληφθεί πολλές φορές.

Τέλος, σε ό,τι αφορά το πρόβλημα του καταμερισμού της κυκλοφορίας στο δίκτυο στη βάση της στοχαστικής ισορροπίας του χρήστη, η επιλογή μίας κατάλληλης τιμής για το συντελεστή διασποράς θ, η οποία θα μπορεί να περιγράψει επαρκώς τα συμπεριφορικά χαρακτηριστικά των μετακινούμενων καθώς και τα τοπολογικά και λειτουργικά χαρακτηριστικά του δικτύου είναι ιδιαιτέρως δύσκολη. Σε αυτό το πλαίσιο, η διαθεσιμότητα πραγματικών δεδομένων κρίνεται απαραίτητη για την εκτίμηση του θ, ανεξάρτητα από την ακριβή μέθοδο εφαρμογής του. Σε γενικές γραμμές, μπορούν να αναγνωριστούν δύο περιπτώσεις: (α) η χρήση μίας και μοναδικής τιμής θ στο σύνολο του δικτύου (θεωρώντας ομοιόμορφη και ανεξάρτητη από το εκάστοτε ζεύγος προέλευσης - προορισμού συμπεριφορά των μετακινούμενων), ή (β) η χρήση μίας δομημένης σχέσης για το συντελεστή διασποράς (η οποία συνυπολογίζει την εξαρτημένη από την απόσταση στοχαστικότητα των ζευγών προέλευσης - προορισμού) (Haghani et al., 2016). Μολονότι η πρώτη περίπτωση απαντάται πιο συχνά, η δεύτερη επιλογή είναι σε θέση να αυξήσει την ακρίβεια του μοντέλου σε πραγματικά δίκτυα, αυξάνοντας όμως παράλληλα και την αντίστοιχη υπολογιστική προσπάθεια. Κατά συνέπεια, αναφορικά με τα εγγενή χαρακτηριστικά του δικτύου, η επιλογή της τιμής θ θα πρέπει να είναι αντιπροσωπευτική του επιθυμητού επιπέδου στοχαστικότητας που ενσωματώνεται στο μοντέλο.

ΕΠ.7 Προτάσεις για μελλοντική έρευνα

Παρότι η διαχείριση δικτύου εκτείνεται από την περίοδο που προηγείται έως την περίοδο που έπεται ενός καταστροφικού γεγονότος και περιλαμβάνει ένα εύρος δραστηριοτήτων που στοχεύουν στη διατήρηση της δομικής ακεραιότητας των υποδομών και την ενίσχυση της απόδοσης του συστήματος, το μεγαλύτερο μέρος της βιβλιογραφίας έχει προς το παρόν επικεντρωθεί στη μελέτη των επιχειρήσεων εκκένωσης δικτύου. Το γεγονός αυτό μπορεί να αποδοθεί στη σημασία της εκκένωσης δικτύου σε όρους προάσπισης της ανθρώπινης ζωής και υγείας. Ωστόσο, η ανάγκη για γενικευμένη διαχείριση δικτύου μετά από καταστροφικό γεγονός είναι εξίσου σημαντική. Το γεγονός αυτό προϋποθέτει τη θεώρηση κινήσεων και προς τις δύο κατευθύνσεις κυκλοφορίας προκειμένου να εξυπηρετηθούν διαφορετικές ανάγκες, την εφαρμογή κατάλληλων στρατηγικών διαχείρισης και το συνδυασμό διαφορετικών μέτρων απόδοσης προκειμένου αυτά να ανταποκρίνονται στους στόχους που τίθενται, καθώς και τη θεώρηση της συμπεριφοράς των μετακινούμενων σε όρους επιλογής διαδρομής προκειμένου να αποτυπώνονται με ρεαλιστικότερο τρόπο τα πρότυπα μετακίνησης που παρατηρούνται στην πράξη. Υπό αυτή την έννοια, η βιβλιογραφία δεν έχει να επιδείξει, προς το παρόν, ένα σημαντικό αριθμό μελετών οι οποίες να επιχειρούν μία ολιστική προσέγγιση επί του θέματος, ειδικά όταν πρόκειται να ληφθεί υπ' όψιν τόσο η φάση που προηγείται, όσο και αυτή που έπεται της καταστροφής. Πράγματι, η διακριτοποίηση του πλαισίου διαχείρισης των καταστροφών μπορεί να διευκολύνει στη μελέτη των επιμέρους επιχειρήσεων, αλλά στερείται ρεαλισμού τόσο σε θεωρητικό, όσο και σε επιχειρησιακό / τακτικό επίπεδο. Στην πράξη, αυτό θα οδηγήσει, κατά πάσα πιθανότητα, στην αποκάλυψη ασυνεπειών κατά την εφαρμογή στη χρονική στιγμή της ενοποίησης των επιμέρους πλαισίων. Συνεπώς, η μελέτη ενός συγκεκριμένου είδους επιχείρησης, παρότι απαραίτητη για την απόκτηση εις βάθους γνώσης, δεν επαρκεί σε όρους προετοιμασίας και σχεδιασμού για την εφαρμογή, καθώς αυτή προϋποθέτει τη θεώρηση διαφορετικών πτυχών του προβλήματος και τη συνέχεια υποθέσεων και δράσεων.

Μία ακόμα ερευνητική περιοχή η οποία χρήζει περαιτέρω μελέτης αφορά στις συμπεριφορικές παραμέτρους που εμπλέκονται στις ατομικές και μαζικές αντιδράσεις που επιδεικνύονται κατά τη διάρκεια καταστάσεων έκτακτης ανάγκης γενικά, και εκκενώσεων δικτύου ειδικότερα. Οι έως τώρα έρευνες οδηγούν στο συμπέρασμα πως η απόφαση για εκκένωση εξαρτάται σε μεγάλο βαθμό από την αντίληψη της επικείμενης απειλής ως πραγματικής και την αξιολόγηση αυτής ως προς τις συνέπειες που θα επιφέρει. Παράλληλα, ο διαθέσιμος χρόνος αντίδρασης, η ύπαρξη σχεδίου έκτακτης ανάγκης και η θέση των μελών της οικογένειας αξιολογούνται ως εξίσου σημαντικές παράμετροι (Helsloot & Ruitenberg, 2004). Πέραν της απόφασης για εκκένωση, όμως, τα χαρακτηριστικά αυτά εμπλέκονται και στη διαδικασία επιλογής διαδρομής, επηρεάζοντας με αυτόν τον τρόπο το σύνολο της διαδικασίας εκκένωσης. Επιπλέον, σε περιοχές που είναι επιρρεπείς σε καταστροφές, οι κοινωνίες μπορεί να αναπτύξουν "υπο-κουλτούρες καταστροφής" ("disaster sub-cultures"), με τον όρο να αναφέρεται στην πολιτισμική προσαρμογή σε επαναλαμβανόμενες απειλές (Granot, 1996). Οι "υπο-κουλτούρες καταστροφής" διαφοροποιούνται με βάση τον κίνδυνο και προϋποθέτουν την αναδιοργάνωση των κοινωνικών ρόλων ώστε αυτοί να ανταποκρίνονται σε συγκεκριμένες συνθήκες (Granot, 1996). Η αναδιοργάνωση της κοινωνίας, ωστόσο, δεν συνεπάγεται κατ' ανάγκη και καλύτερη αντιμετώπιση των καταστροφικών φαινομένων αφού κάτι τέτοιο μπορεί να διακυβεύεται από μία ψευδή αίσθηση ασφάλειας ή την επανάληψη παρελθόντων λαθών (Granot, 1996). Υπό αυτή την έννοια, μία δυσμενής έκφραση της "υπο-κουλτούρας καταστροφής" μίας περιοχής θα μπορούσε να είναι το σύνδρομο του "ψεύτη βοσκού" ("cry wolf" syndrome), το οποίο αναφέρεται στην άρνηση ενός συνόλου ατόμων να συμμορφωθούν προς τις επίσημες οδηγίες και προτροπές εξαιτίας προηγούμενης επανειλημμένης συμμόρφωσης σε λάθος συναγερμούς (Sorensen & Sorensen, 2007). Η συμμόρφωση προς τις οδηγίες, ωστόσο, δεν εξαρτάται μόνο από τη διάθεση κάποιου να τις ακολουθήσει, αλλά και από την πραγματική ικανότητά του να το πράξει. Άτομα που χρήζουν βοήθειας (π.χ. ηλικιωμένοι και παιδιά, άνθρωποι με αναπηρίες, προβλήματα σωματικής ή πνευματικής υγείας, άνθρωποι με περιορισμένους οικονομικούς πόρους, τουρίστες, έγκλειστοι σε σωφρονιστικά ιδρύματα κλπ) τείνουν να εμφανίζουν μικρότερα ποσοστά εκκένωσης σε σχέση με τον υπόλοιπο πληθυσμό (Turner et al., 2010). Κάτι τέτοιο μπορεί να οδηγήσει σε ασυμφωνία μεταξύ των σχεδίων εκκένωσης που έχουν εκπονηθεί και των παρατηρήσεων που γίνονται στην πράξη, καθώς ο σχεδιασμός μπορεί να αφορά στη μέγιστη δυνατή ζήτηση, ενώ ο πραγματικός αριθμός των μετακινούμενων να είναι αρκετά μικρότερος (Turner et al., 2010). Σε μία τέτοια περίπτωση είναι πιθανή μία σπατάλη πόρων, ενώ παράλληλα τίθεται το ζήτημα της ανεπάρκειας του σχεδίου εκκένωσης να εκπληρώσει το σκοπό της μεταφοράς του συνόλου του πληθυσμού σε ασφαλές καταφύγιο. Από την άλλη πλευρά, πολλές μελέτες (e.g. Bish & Sherali, 2013; Afshar & Haghani, 2008; Sbayti & Mahmassani, 2006) έχουν υποδείξει το ακριβώς αντίθετο, ότι δηλαδή η ζήτηση μπορεί να υπερβεί τη χωρητικότητα του δικτύου υπό συνθήκες έκτακτης ανάγκης.

Είναι, επομένως, φανερό ότι η μέχρι τώρα αδυναμία ενσωμάτωσης των συμπεριφορικών χαρακτηριστικών των μετακινούμενων στα διακριτά βήματα της διαδικασίας σχεδιασμού (εκτίμηση της ζήτησης, επιλογή προορισμού, επιλογή διαδρομής) εισάγει αβεβαιότητα στην όλη προσπάθεια διαχείρισης του δικτύου. Το γεγονός αυτό μπορεί να αποδοθεί τόσο στον εξατομικευμένο χαρακτήρα της διαδικασίας λήψης αποφάσεων, όσο και στην έλλειψη διαθέσιμων στοιχείων και στις δυσκολίες που προκύπτουν κατά τη χρήση τους. Συγκεκριμένα, τόσο οι έρευνες δηλωμένης, όσο και οι έρευνες αποκαλυπτόμενης προτίμησης υπήρξαν πάντα η κύρια πηγή συμπεριφορικών δεδομένων εκκένωσης δικτύου. Παρά την αξιοπιστία τους, όμως, τα δεδομένα αποκαλυπτόμενης προτίμησης θα ήταν προτιμότερο να μη χρησιμοποιούνται ως δείκτες πρόβλεψης για περιστάσεις διαφορετικές από αυτές με τις οποίες σχετίζονται (Gudishala & Wilmot, 2010), ενώ τα δεδομένα δηλωμένης προτίμησης μπορεί να αποδειχτεί ότι βρίσκονται σε ισχνή αντιστοιχία με τις συμπεριφορές που απαντώνται στην πράξη και θα ήταν προτιμότερο να αντιμετωπίζονται ως προσδοκίες συμπεριφοράς παρά ως προθέσεις (Kang et al., 2007). Κατά συνέπεια, οι συμπεριφορικές διαστάσεις της εκκένωσης δικτύου έχουν μελετηθεί μέχρι στιγμής από μία μάλλον ποιοτική σκοπιά (Hsu & Peeta, 2013; Chiu & Mirchandani, 2008). Θα πρέπει, επομένως, να δοθεί έμφαση στη γενίκευση των προτύπων συμπεριφοράς που παρατηρούνται στην πράξη και στην μεθοδολογικά αξιόπιστη ποσοτικοποίηση και ενσωμάτωσή τους στη διαδικασία προτυποποίησης της διαχείρισης δικτύου.

Επιπλέον, σε περιπτώσεις καταστροφών, ο ρόλος της πληροφορίας έχει αναγνωριστεί ως ιδιαιτέρως σημαντικός (Quarantelli, 2007). Συγκεκριμένα, έχει παρατηρηθεί αύξηση των ποσοστών συμμόρφωσης στις περιπτώσεις κατά τις οποίες η πληροφορία που μεταδίδεται, εκλαμβάνεται ως ακριβής και πλήρης (Perry & Lindell, 2003), ενώ, αντίθετα, η ανακρίβεια και η ανεπάρκεια πληροφοριών φαίνεται πως οδηγεί σε εφησυχασμό και δυσμενείς ενέργειες (Jaeger et al., 2007). Υπό αυτή την έννοια, η χρήση διαφορετικών πηγών πληροφορίας όπως αυτές που χρησιμοποιούνται ή προτείνονται από τις πλατφόρμες των έξυπνων συστημάτων μεταφορών (intelligent transportation system (ITS)), τα μέσα μαζικής ενημέρωσης και τα κοινωνικά δίκτυα θα μπορούσαν να βοηθήσουν στη διαχείριση καταστροφικών γεγονότων παρέχοντας σύγχρονη ενημέρωση, καθοδήγηση και συστάσεις προς τους μετακινούμενους καθώς και ανατροφοδότηση προς τα ενδιαφερόμενα μέρη. Εκτός από την εκκένωση δικτύου, ωστόσο, η παροχή πληροφοριών μπορεί να βοηθήσει και σε άλλα είδη επιχειρήσεων: το 2008, μία δημοσκόπηση 24 κυβερνητικών διευθυντικών στελεχών διαχείρισης κρίσεων στις ΗΠΑ αποκάλυψε ότι, παρά τη γενικά καλή απόδοσή της, η τεχνολογία της πληροφορίας (information technology (IT)) είναι περισσότερο αποτελεσματική κατά τη φάση απόκρισης (Reddick, 2011). Παράλληλα, η κάλυψη των μέσων μαζικής ενημέρωσης έχει αναγνωριστεί πως έχει σημαντική επίδραση στην αντίληψη των καταστροφικών φαινομένων και στην απόκριση σε αυτά (Houston et al., 2014). Οι ίδιοι συγγραφείς τάσσονται επίσης υπέρ της χρήσης των μέσων κοινωνικής δικτύωσης κατά τη διάρκεια καταστάσεων έκτακτης ανάγκης εξαιτίας της ικανότητας αυτών να παρέχουν σύγχρονη επικοινωνία διπλής κατεύθυνσης. Ωστόσο, προσοχή θα πρέπει να δοθεί όχι μόνο στη διαθεσιμότητα της πληροφορίας, αλλά και στο είδος και την ποιότητα αυτής. Η πληροφορία θα πρέπει γενικά να είναι περιεκτική (Leidner et al., 2009), ενώ οι αμφιβολίες σχετικά με την ακρίβεια και την αξιοπιστία της πληροφορίας που αντλείται από τα κοινωνικά δίκτυα και το πλήθος (crowd-sourcing) έχουν οδηγήσει σε διστακτικότητα των ενδιαφερόμενων μερών να τη χρησιμοποιήσουν (McCormick, 2016). Συγκεκριμένα, η ακρίβεια της πληροφορίας μπορεί να διακυβευθεί από πρόθεση, υπερβολή ή λάθος: κάτι τέτοιο θα μπορούσε να ελαττωθεί με τη χρήση αξιόπιστων πηγών ή με την επιβεβαίωση των πληροφοριών που λαμβάνονται από τα δίκτυα (Heinzelman & Waters, 2010).

Σε κάθε περίπτωση, η πληροφορία που μεταδίδεται από πάνω προς τα κάτω (από τις αρχές προς τον πλήθος) είναι χρήσιμη για τη μετάδοση των επιθυμητών μηνυμάτων, ενώ η επικοινωνία δύο κατευθύνσεων (από τις αρχές προς τον πλήθος και το αντίστροφο) έχει τη δυνατότητα να αυξήσει την αποδοτικότητα της διαχείρισης καταστροφών. Κάτι τέτοιο, ωστόσο, βρίσκει εφαρμογή μόνο στην περίπτωση κατά την οποία τυχόν εμπόδια που αφορούν στη συσσώρευση, επεξεργασία, μετάδοση και λήψη πληροφοριών έχουν, τουλάχιστον έως ένα βαθμό, ξεπεραστεί. Κατά συνέπεια, η διαμόρφωση και εφαρμογή κατάλληλων εργαλείων προς αυτή την κατεύθυνση μπορεί να ωφελήσει όλα τα βήματα της διαδικασίας που εκτείνονται από τη συλλογή και κατηγοριοποίηση των διαφόρων τύπων δεδομένων έως τον εντοπισμό και την απόρριψη ψευδών ή αχρείαστων πληροφοριών και τη μετατροπή των υπολοίπων σε ακριβείς και εύκολα κατανοητές μορφές στη βάση των στοχευόμενων αποδεκτών. Όπως έχει διευκρινιστεί ήδη, η σάρωση των πληροφοριών είναι ιδιαιτέρως σημαντική στην περίπτωση που εμπλέκονται στη διαδικασία τα μέσα κοινωνικής δικτύωσης ή γίνεται άντληση πληροφοριών από το πλήθος, ενώ σε ό,τι αφορά τα μέσα μαζικής ενημέρωσης, η δραματοποίηση ή η μετάδοση λανθασμένων πληροφοριών θα πρέπει να αποκλειστεί. Η εξασφάλιση της αξιοπιστίας της πληροφορίας είναι προαπαιτούμενο για την υιοθέτηση της τεχνολογίας της πληροφορίας στη διαχείριση καταστροφών, με τη διαθεσιμότητα των απαιτούμενων πόρων για την απόκτηση των σχετικών υποδομών και συσκευών (ειδικά στην περίπτωση των έξυπνων συστημάτων μεταφορών) να έπεται. Παρ' όλ' αυτά, η έρευνα στον τομέα του έγκαιρου εντοπισμού ψευδών πληροφοριών και της αποτροπής διάδοσής τους είναι πολύ περιορισμένη (Halse et al., 2018), ενώ επίσης, δεν απαντώνται, μέχρι στιγμής, μελέτες οι οποίες να αξιολογούν την επίδραση των έξυπνων συστημάτων μεταφορών, των κοινωνικών δικτύων, των μέσων μαζικής ενημέρωσης και της άντλησης πληροφοριών από το πλήθος στην πραγματική απόδοση του δικτύου.

Τέλος, κατά την αξιολόγηση της απόδοσης του δικτύου, το επίκεντρο της προσοχής σταδιακά στρέφεται στην υποκείμενη βάση, με ρεαλιστικότερη απεικόνιση των συνθηκών που επικρατούν μετά από καταστροφικό γεγονός και σενάρια μερικών και ολικών βλαβών να παρουσιάζονται ολοένα και συχνότερα στη βιβλιογραφία. Ωστόσο, δεν έχουν αναπτυχθεί, προς το παρόν, εξεζητημένα μοντέλα τα οποία θα μπορούν να συνυπολογίσουν τις αλληλεπιδράσεις που παρουσιάζονται στον πραγματικό κόσμο τόσο μεταξύ των επιμέρους στοιχείων του δικτύου (dependencies), όσο και μεταξύ διακριτών συστημάτων (inter-dependencies). Πράγματι, η υπόθεση της ανεξαρτησίας των βλαβών μεταξύ των συστημάτων ή των στοιχείων τους αναμένεται, εν τέλει, να απορριφθεί, δίνοντας τη θέση της στη θεώρηση των πολύπλοκων σχέσεων που αναπτύσσονται μεταξύ τους. Με αυτόν τον τρόπο θα επιτευχθεί μία εις βάθος κατανόηση της δυναμικής των συστημάτων, με ακριβέστερη αναπαράσταση αυτών και βελτιωμένες εκτιμήσεις απόδοσης. Ωστόσο, σε ό,τι αφορά τη διαχείριση καταστροφών, η θεώρηση των αλληλεπιδράσεων μεταξύ των συστημάτων και των στοιχείων τους βρίσκεται ακόμη σε πολύ αρχικό στάδιο εφόσον η ενσωμάτωση τέτοιων υποθέσεων στη διαδικασία προτυποποίησης είναι, μέχρι στιγμής, εξαιρετικά περιορισμένη.

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List of abbreviations & acronyms

CNL	Cross - Nested Logit
CNDP	Continuous Network Design Problem
CR	Crossover Rate
DNDP	Discrete Network Design Problem
DUE	Deterministic User Equilibrium
EA	Evolutionary Algorithm
GA	Genetic Algorithm
GEV	Generalized Extreme Value
GNL	Generalized - Nested Logit
IAP	Implicit Availability / Perception
ICT	Information and Communication Technologies
IIA	Independence of Irrelevant Alternatives
IID	Independently and Identically Distributed
IPM	Iterative Penalty Method
IT	Information Technology
ITS	Intelligent Transportation Systems
LK	Logit Kernel
MNDP	Mixed Network Design Problem
MNL	Multinomial Logit
MR	Mutation Rate
NDP	Network Design Problem
OD	Origin - Destination
OD-A	Origin - Destination Pair Accessibility
OF	Objective Function
PCL	Paired Combinatorial Logit
PSL	Path - Size Logit
RP	Revealed Preference
SD	Satisfied Demand
SO	System Optimal
SP	Stated Preference
SUE	Stochastic User Equilibrium
TNTT	Total Network Travel Time
TT	Travel Time
UE	User Equilibrium
USGS	United States Geological Survey

1. Introduction

1.1 Disasters and disaster management

The word *"disaster"* is, nowadays, becoming increasingly prevalent. Despite some skepticism about the term's over-use (see for example Furedi (2007)), most analysts seem to agree that natural disasters, especially climate change-related ones, have increased in the recent years in number, magnitude and impacts (Baas et al., 2008). Human-induced disasters are also of concern; technological accidents as well as intentional attacks seem to evolve along with the struggle for economic and societal growth and prosperity.

However, and despite any possible intuition, there is no general consensus on the definition of what constitutes a "disaster". As Quarantelli (1985), quoting Barkun (1974), remarks "...a disaster is perhaps easier to recognize than it is to define". Quarantelli (1985) distinguishes between seven approaches, frequently used for the categorization of a phenomenon as a disaster. These may be summarized as follows:

- *Physical agents:* Disasters are equated with physical phenomena, such as earthquakes, floods, wildfires, explosions etc. Emphasis is placed on the cause of each event, with distinction made between natural and human-induced catastrophes.
- *Physical impact:* Disasters are equated with the physical impact they induce on the environment they affect. As such, certain disaster characteristics, including the occurrence frequency, the location of the strike and the duration of the phenomenon, may interfere with the impact, which, in any case, has to be discernible.
- *Assessment of the physical impact:* Disaster categorization entails a certain benchmark or threshold regarding the impact of the phenomenon to be surpassed. In this respect, a set of criteria is set and, in order for the characterization to hold, the effects must be assessed as notable.
- *Social disruption as a result of the physical impact:* The physical impact is not sufficient per se for the characterization of a phenomenon as a disaster. This is rather used as an indicator of the social disruption it implies. Compared to the previous approach, the focus here lies on the social implications induced by the event and whether these are perceived as significant, and not on the actually incurred, quantifiable physical damage.
- *Social construction of reality:* Disasters are defined in subjective, rather than objective, terms. Indeed, the often observed lack of correlation between the physical impact of a phenomenon and the social actions undertaken for its prevention and / or management

leads to the conclusion that, it is the perception of danger that drives the social implications and not the actual physical consequences.

- *Political definition:* Disaster characterization is straightforwardly dependent upon the political decision-making. The relation is indeed present, since official disaster declarations can considerably interfere with the actions undertaken and the resources implemented in all disaster management stages, extending from mitigation and preparedness to response, recovery and reconstruction.
- *Imbalance in the demand - capability ratio:* Disasters can be recognized by the imbalance caused when the demand for action exceeds the response capability. Due to the impending threat to highly-valued assets (life, property etc.), the need for collective action assumes an urgent, non-routine character.

Quarantelli (1985) points out a shift in the definition of "disaster" from merely physical terms to social situational ones. In this context, **Table 1.1** summarizes official definitions of the word "disaster", as these are provided by institutional organizations and agencies. From the table, it can be concluded that, most modern definitions adopt a social disruption dimension (4th approach) (e.g. International Federation of Red Cross and Red Crescent Societies, 2019b; European Environment Agency, 2019; United Nations, Department of Humanitarian Affairs, 1992; Emergency Management Australia, 1998). However, definition of "disaster" in terms of its causal origin (1st approach) (e.g. Emergency Events Database, 2019; British Columbia - Emergency Program Act, 2019; Federal Emergency Management Agency, 2019), physical impact (2nd approach) (e.g. United Nations Office for Disaster Risk Reduction, 2019a), impact assessment (3rd approach) (e.g. European Environment Agency, 2019; United Nations, Department of Humanitarian Affairs, 1992; British Columbia - Emergency Program Act, 2019; State of Queensland - Disaster Management Act, 2018), political decision-making (6th approach) (e.g. Federal Emergency Management Agency, 2019), and inability of the affected communities to cope with the increased demand for action (7th approach) (e.g. Emergency Events Database, 2019; International Federation of Red Cross and Red Crescent Societies, 2019b; European Environment Information and Observation Network, 2019; Federal Emergency Management Agency, 2019; United Nations Office for Disaster Risk Reduction, 2019a) are also present, with most definitions, however, providing a combination of two or more approaches.

From all the above, it can be concluded that definition of "disaster" is mainly a matter of perception; conceptualization leans towards subjectivity rather than objectivity. Indeed, in February 07-14, 2017, heavy rainfall across the State of California in the US caused substantial damage to the Oroville Dam's main and emergency spillways. Due to the extensive and fast-paced ground erosion, the authorities assessed the possibility of the spillways' gate and / or weir collapse to be significant and ordered the evacuation of 188,000 residents near Lake Oroville. The collapse was eventually prevented and the losses were limited to the structural degradation of the spillways and the compulsory shutdown of the nearby hydroelectric plant for a few days. Despite the relatively low physical consequences though, the Oroville Dam incident was considered to be a major disaster; this can be related to the level of threat that a possible collapse would pose, with disaster characterization in this case straightforwardly linked to the 5th approach indicated by Quarantelli (1985).

A sole definition of "disaster" is therefore ambiguous. In general, a disaster is associated with the impact of a phenomenon on tangible and intangible, but, in any case, highly-valued assets, as well as with the threat to those assets, and it is dependent upon the ability of the society to cope with the event itself and any implications thereof. For practical purposes, though, it is useful to develop a more straightforward view of what constitutes a disaster and identify any possible differences between the individual frameworks.

In this context, a frequently made distinction is between natural and human-induced disasters. Apart from the causal differences, natural and man-made disasters generally distinguish from one another on the basis of: (a) the extent and, (b) the magnitude of the impact induced and, (c) the occurrence timing and evolution of the phenomenon. With respect to the first parameter, natural disasters tend to have an extensive impact area (X. Chen et al., 2012), which may be spatially uneven and variable with time (Barrett et al., 2000). Man-made disasters, on the other hand, can be pinpointed in space, with their impact extending with almost radial symmetry to their surroundings (X. Chen et al., 2012; Barrett et al., 2000). In terms of the impact magnitude, natural disasters generally have a more smooth effect over the stricken area, while the impact of man-made disasters is heightened at the focal node and gradually fades away as the distance from the epicenter increases (X. Chen et al., 2012). Last, while some natural disasters can be anticipated, with individual parameters of their evolution continuously monitored and assessed, man-made disasters are inherently unexpected events, with any possible information about them not sufficiently raising the certainty and confidence in what it is about to happen (Hamza-Lup et al., 2008).

Despite the exact concept though, the potentially catastrophic effects of disasters necessitate the formulation of appropriate management frameworks and the designation of respective courses of action for the enhancement of system resilience. In this context, the origins of *disaster management* can historically be traced back to the Second World War (1939 - 1945) and the subsequent period of the Cold War (1947 - 1991) (Pearce, 2003; Dynes, 1994). During these first stages, disaster management was mainly influenced by the military operations, with disasters viewed and approached as "enemy attacks". The accompanying fundamental assumptions of emergency planning could be summarized in the "triple C's" dogma: chaos, command and control (Dynes, 1994); that is, disasters were assumed to cause chaos that only command and control could sufficiently handle. This type of response probably stemmed from a deep-seated belief that the military could effectively deal with analogous threatening situations; as such, organizations involved in emergency management were expected to adopt a para-military organization structure in order to cope with the needs arising (Dynes, 1994). However, Dynes (1994) considers this approach to be grounded on unrealistic assumptions and, thus, to be inapplicable and ineffective in practice; the author suggests a different kind of "triple C's" model, based on continuity, cooperation and coordination. Indeed, in modern societies the focus has shifted from the strict military "triple C's" construction to the more flexible community-oriented form.

Table 1.1 Definitions of disaster

Organization / Agency	Definition of disaster
Emergency Events Database (2019)	Situation or event which overwhelms local capacity, necessitating a request to national or international level for external assistance. An unforeseen and often sudden event that causes great damage, destruction and human suffering. Though often caused by nature, disasters can have human origins.
International Federation of Red Cross and Red Crescent Societies (2019b)	A sudden, calamitous event that seriously disrupts the functioning of a community or society and causes human, material and economic or environmental losses that exceed the community's or society's ability to cope using its own resources. Though often caused by nature, disasters can have human origins.
European Environment Information and Observation Network (2019)	The result of a vast ecological breakdown in the relations between man and his environment, a serious and sudden event (or slow, as in drought) on such a scale that the stricken community needs extraordinary efforts to cope with it, often with outside help or international aid.
European Environment Agency (2019) United Nations, Department of Humanitarian Affairs (1992)	A serious disruption of the functioning of society, causing widespread human, material or environmental losses, which exceed the ability of affected society to cope using only its own resources. Disasters are often classified according to their cause (natural or man-made).
Emergency Management Australia (1998)	A serious disruption to community life which threatens or causes death or injury in that community and / or damage to property which is beyond the day-today capacity of the prescribed statutory authorities and which requires special mobilization and organization of resources other than those normally available to those authorities.
British Columbia - Emergency Program Act (2019)	A calamity that: (a) is caused by accident, fire, explosion or technical failure or by the forces of nature, and (b) has resulted in serious harm to the health, safety or welfare of people, or in widespread damage to property.
Federal Emergency Management Agency (2019)	An occurrence of a natural catastrophe, technological accident, or human-caused event that has resulted in severe property damage, deaths, and / or multiple injuries. As used in this Guide, a "large-scale disaster" is one that exceeds the response capability of the local jurisdiction and requires State, and potentially Federal, involvement. As used in the Stafford Act, a "major disaster" is "any natural catastrophe [...] or, regardless of cause, any fire, flood, or explosion, in any part of the United States, which in the determination of the President causes damage of sufficient severity and magnitude to warrant major disaster assistance under [the] Act to supplement the efforts and available resources or States, local governments, and disaster relief organizations in alleviating the damage, loss, hardship, or suffering caused thereby."
United Nations Office for Disaster Risk Reduction (2019a)	A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts. The effect of the disaster can be immediate and localized, but is often widespread and could last for a long period of time. The effect may test or exceed the capacity of a community or society to cope using its own resources, and therefore may require assistance from external sources, which could include neighboring jurisdictions, or those at the national or international levels.

Organization / Agency	Definition of disaster
State of Queensland - Disaster Management Act (2018)	A serious disruption in a community, caused by the impact of an event, that requires a significant coordinated response by the State and other entities to help the community recover from the disruption. In this section, serious disruption means: (a) loss of human life, or illness or injury to humans, or (b) widespread or severe property loss or damage, or (c) widespread or severe damage to the environment.

Table 1.2 Definitions of disaster management

Organization / Agency / Author	Definition of disaster management
United Nations Office for Disaster Risk Reduction (2019b)	The organization, planning and application of measures preparing for, responding to and recovering from disasters. Disaster management may not completely avert or eliminate the threats; it focuses on creating and implementing preparedness and other plans to decrease the impact of disasters and “build back better”. Failure to create and apply a plan could lead to damage to life, assets and lost revenue.
International Federation of Red Cross and Red Crescent Societies (2019a)	The organization and management of resources and responsibilities for dealing with all humanitarian aspects of emergencies, in particular preparedness, response and recovery in order to lessen the impact of disasters.
State of Queensland - Disaster Management Act (2018)	Arrangements about managing the potential adverse effects of an event, including, for example, arrangements for mitigating, preventing, preparing for, responding to and recovering from a disaster.
Carter (2008)	An applied science which seeks, by the systematic observation and analysis of disasters, to improve measures relating to prevention, mitigation, preparedness, emergency response and recovery.
Lettieri et al. (2009)	The body of policy and administrative decisions, the operational activities, the actors and technologies that pertain to the various stages of a disaster at all levels.
Peeta et al. (2010)	Disaster management is a multi-stage process that starts with pre-disaster mitigation and preparedness that focus on long-term measures for reducing or eliminating risk, and extends to post- disaster response, recovery and re-construction.

Flexibility in disaster management is dictated by the very nature of the disaster phenomena. As Quarantelli (1985) notes: "In a disaster, there is considerable variation in how the everyday capability / resource and demand / need balance gets unbalanced." In the above statement, Quarantelli (1985) recognizes that catastrophes pose stress to the systems by distorting the previously existing balance between demand and capacity, with the distortion occurring in ways not unilaterally defined. Thus, disasters are inherently stochastic phenomena in terms of both their occurrence and their implications and, as a result, their management must be accordingly adaptive.

In this context, disaster management generally refers to a set of decisions and measures that involve both levels of societal organization (the authorities and the community) and pertain to all disaster phases with the objective of achieving improved system resilience. These steps can generally be defined as prevention, mitigation, preparedness, response and recovery; the first three operations (prevention and mitigation of disaster risks and preparedness) belong to the pre-disaster phase, while the latter two (response and recovery) take place during its aftermath. As such, **Table 1.2** summarizes six definitions of "disaster management" commonly used; as can be seen from the table, the fundamental elements of disaster management, as these were previously outlined, crosscut most definitions.

1.2 The role of transportation networks

During disasters, the role of transportation networks arises as significantly important. Although not at the forefront of emergency management rationale, in cases of catastrophes, transportation networks act as vital lifelines, ensuring network connectivity and providing the necessary, underlying ways for the execution of a series of emergency operations. A list of such operations is provided by the Virginia Transport Policy Institute in relation to the type of disaster considered (**Table 1.3**).

Table 1.3 Disaster-related transportation operations (Victoria Transport Policy Institute, 2016)

Disaster type	Geographic scale	Warning period	Evacuation	Emergency services	Search & rescue	Quarantine	Infrastructure repair
Hurricane	Very large	Days	*	*	*		*
Earthquake	Large	None	*	*	*		*
Tsunami	Very large	Short	*	*	*		*
Flooding	Large	Days	*	*	*		*
Forest fire	Small to large	Usually	*	*	*		*
Volcano	Small to large	Usually	*	*	*		*
Blizzard / ice storm	Very large	Usually		*	*		*
Explosion	Small to large	Seldom	*	*	*		*
Radiation / toxic release	Small to large	Sometimes	*	*		*	
Landslide / avalanche	Small to medium	Sometimes	*	*	*		*

At the same time, transportation networks are themselves vulnerable to structural and functional degradation, with Zimmerman et al. (2007) noting the importance of network's availability and capacity in the effectiveness of post-disaster operations. That, combined with the stochasticity involved in the travelers' behavior and the diverse needs arising, mount the pressure on the need for effective network management. This will, most probably than not, require a re-structuring of network functioning, often in the form of network re-configuration along with the employment of other management strategies. In this context, formulation of appropriate management tools that can account for the network's operational state and the individuals' behavioral aspects and optimally re-structure them to the benefit of overall network functionality will be of significant practical importance. In such settings, these tools can help facilitate the related emergency operations and provide added value to the whole disaster management process.

1.3 Research scope and methodological steps

From all the above it can be concluded that, regardless of the theoretical (with practical implications though) discussion of what constitutes a "disaster" and irrespective of its actual type and consequences (if this is indeed perceived as one), the communities ask for, and are actually in need of, effective countermeasures to ultimately preserve their societal structure and functioning. In this context, the present dissertation focuses on disaster management in transportation networks in the post-catastrophe period. Although many distinct operations may take place in a post-disaster stage (with population evacuation being possibly the most important and well-studied among them, due to its significance in proactively protecting human life and health), this thesis investigates the concept of generalized post-disaster network management. Indeed, in the case of disruptive events, generalized network management appears to be equally essential and practically more frequent. This precludes the investigation of specific disaster operations and focuses on the needs generated by various types of network users through the consideration of bi-directional traffic movements, the integration of appropriate management strategies and performance measures on the basis of the system objectives set and the incorporation of users' route choice behavior.

Network management, as this is realized through the associated network operations, can generally be classified as an instance of the *network design problem (NDP),* which has been recognized as one of the most difficult problems in transportation (Wang et al., 2013; Chootinan et al., 2005; Yang & Bell, 1998). By definition, the NDP involves deciding upon the management strategies implemented on a network for optimizing its performance, while accounting for budget constraints and users' route choice behavior (Wang et al., 2013; Chootinan et al., 2005). Performance enhancement is pursued through either network re-configuration and / or demand re-allocation, while users' behavior is captured by *deterministic user equilibrium (DUE)* or *stochastic user equilibrium (SUE)* principles (Yang & Bell, 1998). Nevertheless, the DUE principle is considered to be inadequate for modeling travel behavior (Prashker & Bekhor, 2004), especially during emergencies (Hsu & Peeta, 2013). Indeed, fluctuations of the network flows on the basis of demand and supply changes over time make it reasonable to assume that stochastic equilibrium models may be more appropriate for real-world problems (Xie & Liu, 2014; Prashker & Bekhor, 2004). Despite the flexibility of the NDP in incorporating randomness in its formulation, though, current research efforts have until now failed accounting for stochasticities (Chen et al., 2011).

In this context, the present thesis aims at advancing the state-of-the-art in disaster management by providing a framework that supports and promotes the enhancement of network functionality in an integrated manner. The thesis distances itself from the consideration of specific network operations and examines network functioning from a wider perspective. In order to do so, the framework explicitly considers the operational state of the network and users' behavioral patterns and attempts a system re-organization on the basis of defined objectives. This is achieved through the use of appropriate management strategies, the development of a multi-aspect performance measure, the formulation of suitable hypotheses regarding route construction and route choice and the selection of an appropriate analysis concept. The dissertation ultimately provides an integrated conceptual and mathematical framework for efficiently handling the diverse needs arising in the period following a catastrophe. The framework can be used as a planning tool by transportation professionals and stakeholders and adds a higher degree of realism in the decision-making process by explicitly accounting for some of the stochasticities that are either way present in transportation management, but possibly exacerbated in a post-disaster setting.

In accordance with the delineated research scope, the distinct methodological steps followed in the dissertation may be summarized as:

- Extensive review of the disaster management literature, with emphasis placed on the inter-related aspects of network performance estimation and network operations' planning. Recent advances in the field are identified and research areas that offer possibilities for further investigation are revealed.
- Overview of existing route choice models and path generation methods. The necessary background is provided in order to help decide upon the most appropriate combination of these parameters, with respect to the characteristics of the post-disaster environment and the planning objectives set.
- Development of a novel conceptual framework that integrates various problem aspects of generalized network management. This step offers a sound theoretical and methodological basis for the planning of operations in the aftermath of a catastrophe with the overall objective of network performance enhancement.
- Formulation of the associated mathematical models that correspond to the conceptual framework delineated. Expressions are constructed that realize the model's theoretical conception and constitute the essence of the research conducted.
- Development of efficient optimization algorithms for handling the aforementioned mathematical models. Powerful solution methodologies (such as metaheuristics) are exploited, that can reduce the computational burden associated with network management problems while providing high-quality, robust results.

- Validation of the previously formulated conceptual framework, planning models and solution algorithms through their application on test networks under different disaster scenarios and problem hypotheses.

It can, thus, be concluded that the dissertation offers a structured approach towards post-disaster network management, extending from the conceptual conception and mathematical formulation of the integrated framework, to the development of advanced solution methodologies and the application of these on test networks to showcase their efficiency.

1.4 Structure of the dissertation

The rest of the dissertation is structured as follows:

- The *second* chapter analyzes the problem of disaster management from a transportation perspective. It distinguishes between planning in the pre- and post-disaster phases, accentuating the role of the latter in ensuring overall network functionality. Post-disaster planning is investigated as two separate sub-problems: (a) estimation of network performance, and (b) decision-making and planning of the respective operations. An extensive literature review of these inter-related aspects is conducted, with individual problem features explained and discussed. Classification of the network performance literature is based on: (a) the disaster environment assumed, and (b) the conceptual approach followed, with the first one further analyzed into the disaster type, the network characteristics and the component failure mechanisms assumed, whilst the latter refers to the type of analysis considered, the performance measures used, the dependencies between the network components present, the pre- and post-disaster interventions applied and the objectives set. On the other hand, classification of the operations' planning literature is made according to: (a) the planning scope, and (b) the planning process adopted, with the first term referring to the type of operations employed as well as to their planning and implementation timing, while the second term focuses on the actual decision-making process and comprises the actions determined, the analysis tools used, the strategies and parameters identified and the objectives set.
- The *third* chapter focuses on the traffic assignment problem and offers an overview of route choice models and path generation methods. More specifically, due to the NDP formulation of the post-disaster management problem, and in view of the inadequacy of the deterministic user equilibrium (DUE) principle to realistically capture travel behavior (especially during emergencies), various route choice models based on either logit or probit formulations have been developed. Despite both classes tracing their origins back to utility theory, distinctive differences between them exist, making the features of the models classified under each category more or less desirable from a route modeling perspective. The multinomial logit (MNL) and most of the models belonging to the MNL family are presented in the chapter, with the rest of the MNL-based models as well as the probit ones described in Appendix A. Mathematical programming formulations of stochastic user equilibrium (SUE) are additionally provided. The chapter concludes by describing the implicit and explicit path set construction methods, with explicit

approaches, extending from deterministic and stochastic shortest path-based methods to the constrained enumeration and probabilistic ones, more thoroughly analyzed.

- The *forth* chapter conceptually conceives and constructs the model used for the optimization of network operation in the aftermath of a catastrophic event. The model is formulated as an instance of the mixed network design problem (MNDP); two distinct management strategies (lane reversal and demand regulation), a multi-aspect measure of performance (including travel time, satisfied demand and OD-pair accessibility indices), stochastic user equilibrium (SUE) traffic assignment (according to the paired combinatorial logit (PCL) model) and iterative path generation (following the link penalty approach) are combined under a vulnerability analysis context in order to provide a re-configured network with re-allocated demand so that network performance is maximized. The problem's outline along with its mathematical expression are delineated, with discussion over individual problem aspects supporting the respective assumptions and decisions made. The end of the chapter presents a detailed flowchart of the model's programming steps, as these were realized in MatLab's computing environment.
- The *fifth* chapter discusses the solution methodology adopted. Due to the MNDP structure of the network management model (bi-level formulation with inclusion of both continuous and discrete variables), the convexity of the solution space is not guaranteed. As such, the use of exact solution algorithms is precluded and one must resort to approximation algorithms or metaheuristics to obtain solutions of practical value. In this respect, a genetic algorithm (GA) coupled with a traffic assignment process is used as a solution methodology for the problem at hand. Definition of GAs along with description of their main components and mechanisms, explanation of their differences from traditional methods and analysis of the advantages of their use under the prism of evolutionary computation are provided.
- The *sixth* chapter is engaged in applying the formulated model on a set of case studies with subsequent comprehensive presentation of the analysis results. As such, a test network is used as the basis for a series of analyses to be performed. These can be distinguished into four categories: (a) analyses regarding changes in the network's physical attributes, including changes in network topology (disruption of network nodes and links) and link capacity, (b) analyses regarding modifications of problem parameters, including changes in the values of the penalty factor P (involved in the path generation process) and the dispersion coefficient θ (indicating the variance among drivers and involved in the SUE model), complemented, in the latter case, with analyses performing a deterministic assignment of traffic on the network links according to the deterministic user equilibrium (DUE) and system optimal (SO) principles, (c) analyses regarding fluctuations of the demand between the network's OD pairs, and finally, (d) analyses regarding variations of the weighting coefficients of the upper-level objective function terms (sensitivity analysis). In this respect, the goal of the analyses is twofold: (a) to investigate the algorithm's efficiency and efficacy in enhancing network performance, and (b) to explore the implicit relationship between the problem's optimal solution and

the aforementioned changes in the problem's input parameters. Different types of tables and diagrams are used to demonstrate the analysis results (some of them placed in Appendix C); these regard either the individual case studies or focus on performing comparative evaluations between the distinct experiments. Interpretation and discussion of the results is provided in order to highlight specific problem aspects and, ultimately, reach certain conclusions.

- The *seventh* chapter summarizes the findings of the dissertation and draws the main conclusions from the research conducted. In addition, possible directions for future research are suggested and discussed.

The dissertation concludes with the bibliographic references cited in the text and Appendices A, B and C.

2. Post-disaster transportation network management

2.1 Introduction

Natural and human-induced disasters have always been of concern to societies; their unforeseeable characteristics along with the possibility of human life losses and casualties, the structural degradation of infrastructures and the disruption of activities, pose a threat to social and economic continuity and growth. This impact appears to have increased in the recent years (Baas et al., 2008); the size and density of modern communities and their dependency on sophisticated, yet vulnerable, infrastructures have critically contributed in this direction. Indeed, civil infrastructures provide added value and competitive advantage to an area and, inevitably, a catastrophic event affecting them may lead to both immediate and long-term losses. In this context, susceptibility of infrastructures to failures may come as a result of their introduction to disaster-prone areas. Critical infrastructures, however, may constitute themselves potential targets for terrorist attacks. In either case, their capacity and serviceability are expected to be reduced in the aftermath of a catastrophe.

The impacts and associated risks of disasters can be mitigated through careful planning; disaster management refers to the organization and management of personnel, resources and infrastructure and the determination of appropriate courses of action towards achieving certain performance objectives. It involves a chain of activities, ranging from performance evaluation and pre-disaster improvement of network resilience to post-disaster response, recovery and re-construction (Peeta et al., 2010). These facts imply that planning for disasters is a multi-aspect process, targeting at different phases, before, during and following a catastrophe. The difficulties arising in this context have also been of interest to the Federal Highway Administration (FHWA), which, as Zimmerman et al. (2007) note, "recognizes the unique challenges posed by the disaster environment on mobility and the safe and secure movement of people and goods". In the same study, Zimmerman et al. (2007) accentuate the importance of the transportation network's availability and capacity in emergency response and evacuation operations. Indeed, transportation networks act as critical lifelines in cases of disasters; while remaining the sole means of ensuring physical access to the affected communities, they additionally support a range of emergency services extending from population evacuation and response operations to supply chains and restoration of activities. It can, thus, be concluded that in a post-disaster setting, the functionality of the surviving network arises as significantly important, while the development and deployment of efficient tools for the planning and management of the associated operations can decisively enhance network performance.

The complex and inherently stochastic nature of post-disaster network management, though, has led to its decomposition into sub-problems; as such, network performance estimation and network operations' planning are two interrelated aspects in the field. The first one sets the basis for all operations' planning, while the second one lies in the core of every disaster management plan. Attention, however, must be paid so that the plans developed for different problem aspects are in accordance with each other, leaving no significant gaps or contradicting assumptions / actions to be revealed though implementation.

2.2 Disaster planning in transportation

According to Peeta et al. (2010), "disaster management is a multi-stage process that starts with pre-disaster mitigation and preparedness that focus on long-term measures for reducing or eliminating risk, and extends to post-disaster response, recovery and re-construction". The pre-disaster planning phase therefore, involves strategic decision-making for risk assessment, infrastructure improvements to reduce vulnerability and enhance system resilience as well as configuration of emergency plans. The post-disaster phase involves performance estimation and tactical and operational decision-making for providing critical emergency response, recovery and re-construction services. **Figure 2.1** illustrates the disaster planning process.

Figure 2.1 The disaster management process (Peeta et al., 2010)

Pre- and post-disaster planning tasks are interrelated. Efficient pre-disaster planning involves the design of new, failure-resistant infrastructures as well as investment decisions in the form of reinforcement or retrofit actions that allow the structural integrity and survivability of network components to be enhanced; to that end, post-disaster operations set the prioritization criteria in light of potential budgetary constraints (Peeta et al., 2010). However, experience has shown that prevention steps are often inadequate; the characteristics of the catastrophe, the physical and functional state of the infrastructure and population's conformance to emergency plans are uncertain and may lead to a rapid degradation of the transportation system's operational performance. In addition, even detailed prevention planning is difficult to deploy in full due to limitations in resources and increased implementation costs. In that sense, post-disaster planning should embrace the stochasticities entailed and adapt to the prevailing conditions by providing short- and mid-term actions that facilitate the operations undertaken.

2.2.1 Configuration of disaster management plans

As already explained, in cases of disasters, transportation networks should be able to provide the necessary support for emergency operations. Either in the form of conceptual plans or real-time management, data on network condition and the post-disaster environment should be used to determine the appropriate remedial actions to be deployed. However, in the aftermath of a catastrophe, network infrastructure may suffer from physical and / or functional degradation. This is particularly true for natural disasters, which tend to cause extensive damages over a broader area (Jenelius & Mattsson, 2012) but can also be true for man-made disasters (Murray-Tuite & Wolshon, 2013). However, the latter usually cause some sort of disruption to a limited part of the network (Jenelius & Mattsson, 2012).

What is important from a managerial point of view is the estimation of post-disaster network performance since this will set the basis for the subsequent planning and implementation of the necessary operations; a critical threshold must be preserved to ensure the safe and secure movement of people and goods. The next step involves the core of the decision-making process; depending on the nature and the impact of the disaster, appropriate courses of action are selected, planned and deployed. These may vary from population evacuation to network restoration activities. In this context, the literature on post-disaster network management can broadly be divided into two categories:

- Estimation of post-disaster network performance.
- Decision-making and planning of post-disaster operations.

In order to make a performance assessment, one must first define appropriate measures and the necessary models for their estimation or measurement. The outcome can then be used for the decisions that need to be made with respect to the management of the surviving transportation network.

2.3 Network performance estimation

Estimation of network performance is an important first step during operations' planning. Classification of the associated literature is based on the framework of **Figure 2.2** and includes (a) the disaster environment assumed, and (b) the conceptual approach followed. Indeed, disaster type, network characteristics and component failure mechanisms are important parameters in performance estimation, with the latter assessed according to different conceptual approaches. Modeling efforts are dictated by the type of analysis considered, the performance measures used, the dependencies between network components present, the pre- and post-disaster interventions applied and the objectives set. In this context, **Table 2.1** classifies existing work with respect to the type of analysis conducted and the way failure is represented while **Table 2.2** illustrates the performance measures considered in each study.

2.3.1 Disaster environment

The disaster environment sets the underlying assumptions for estimating network performance. These include the type of disaster considered, the network characteristics assumed and the way component failures are modeled.

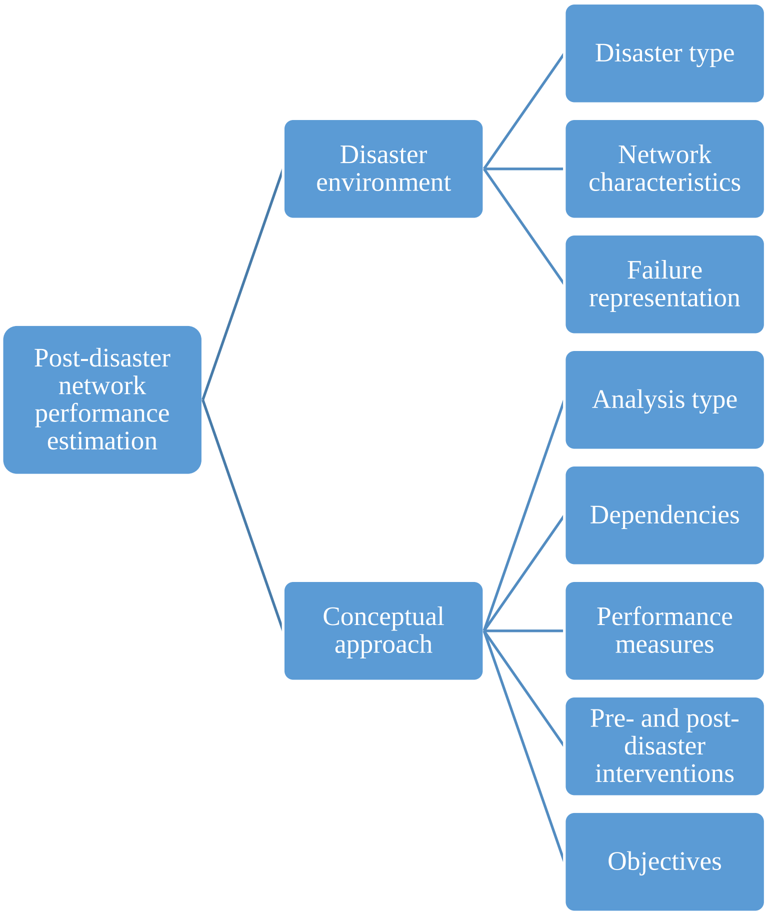


Figure 2.2 Classification framework for post-disaster network performance estimation

2.3.1.1 Disaster type

Since performance is generally related to the impacts of a catastrophe, it could be argued that the actual type of disaster considered is of limited practical importance. In this context, many studies assume a generic type of disaster (e.g. Dehghani et al., 2014; El-Rashidy & Grant-Muller, 2014; Taylor & Susilawati, 2012; Nagurney & Qiang, 2009; Ukkusuri & Yushimito, 2009). However, in cases where the impact is closely related to particular disaster characteristics, the phenomenon itself arises as significant; for example, Kiremidjian et al. (2007b) use earthquake records to evaluate the structural and operational loss of a bridge network, Nabian & Meidani (2018), Guo et al. (2017), Dong et al. (2014) and Bocchini & Frangopol (2011) exploit seismic fragility curves as inputs in bridge network performance analysis and Kermanshah & Derrible (2016) use the United States Geological Survey (USGS) ShakeMaps to simulate the impact of earthquakes on roadway infrastructure. Overall, earthquakes constitute a commonly considered disaster type (e.g. Hu et al., 2016; Zhang & Wang, 2016; Edrissi et al., 2015; Edrissi et al., 2013; Nagae et al., 2012; Kiremidjian et al., 2007a; Kiremidjian et al., 2007b; Pitilakis et al., 2006).

2.3.1.2 Network characteristics

In performance evaluation, the network itself sets the basis for the formulation of the problem. Assumptions on network characteristics define the initial network configuration, its connectivity settings, the state of individual components and network's post-disaster requirements; for instance, the lower traffic volumes of rural networks point towards performance being related to accessibility (e.g. Taylor & Susilawati, 2012), while, the different operations and the limited connectivity and bypass options of railways may lead to distinct performance interpretation (e.g. Johansson & Hassel, 2010).

In this context, past research has focused on generalized transportation networks, distinguished into *urban* (e.g. Ganin et al., 2017; Donovan & Work, 2015; Balijepalli & Oppong, 2014; Tuzun Aksu & Ozdamar, 2014; B. Chen et al., 2012; Yang & Qian, 2012; Bono & Gutiérrez, 2011), *regional* (e.g. Omer et al., 2013; Taylor & Susilawati, 2012), *highway* (e.g. Yang et al., 2013; Günneç & Salman, 2011; Peeta et al., 2010; Matisziw & Murray, 2009; Selçuk & Yücemen, 1999) and *railway* networks (e.g. Johansson & Hassel, 2010; Chang, 2003). Some researchers consider bridges to be the most vulnerable part of the network and, as such, investigate *bridge* networks (e.g. Wang & Jia, 2019; Nabian & Meidani, 2018; Guo et al., 2017; Zhang et al., 2017; Zhang & Wang, 2016; Dong et al., 2013; Nagae et al., 2012; Bocchini & Frangopol, 2011; Karlaftis et al., 2007). In general, network selection can be made on the basis of different criteria, including the type of the transportation mode considered, the geographic and operational characteristics of the network supposed and any specific assumptions made.

2.3.1.3 Failure representation

Network components may refer to links, nodes or both (Ahuja et al., 1993). While most papers assume link failures only, some studies account for node failures as well. In any case, when network nodes are appropriately associated to their adjacent links, the link failure assumption does not pose any restriction to the problem formulation. Indeed, Qiang & Nagurney (2008) assume both link and node failures; link failures are treated by removing the respective links from the network while node failures are treated by removing all the links entering or exiting these nodes.

Failure, on the other hand, does not necessarily imply structural damage. More often, it refers to the reduced ability of a component to fully correspond to its former function and it is, thus, linked to its serviceability. Binary component states (operational or not operational) are usually assumed; this assumption, however, is not always accurate since a component may be partially functional, a condition indicated by some sort of capacity reduction or distance increase (Chang, 2003; Chang & Nojima, 2001). It could be argued, though, that the removal of a damaged link from the network representation is a usual, yet safety-favorable assumption. Günneç & Salman (2011) while assessing network reliability, argue in favor of complete elimination of partially destroyed links, since these may not be accordingly partially operational due to the reluctance of using them. On the other hand, Du & Nicholson (1997) support the use of multiple link capacity degradation scenarios for an accurate estimation of network performance. In the same context, Sullivan et al. (2010) are averse to complete link removal for not being realistic and methodologically sound. In general, these two cases are denoted as *complete* (e.g. Yang et al., 2018; Hu et al., 2016; Kermanshah & Derrible, 2016; Rupi et al., 2014; Tuzun Aksu & Ozdamar, 2014; Edrissi et al, 2013; Knoop et al., 2012; Yang & Qian, 2012; Taylor & D’ Este, 2007) and *partial* (e.g. Wang & Jia, 2019; Zhang et al., 2015; Balijepalli & Oppong, 2014; Dong et al., 2014; Omer et al., 2013; Burgholzer et al., 2012; Snelder et al., 2012; Bocchini & Frangopol, 2011) *component failure* respectively.

With respect to the extent of the disruption assumed, disasters can be separated into localized and wide-scale ones, with the first one affecting a small area, whereas the second one may affect an entire city or region. Transportation accidents, bomb attacks and structure fires are typical examples of the first category, taking place in urbanized environments and causing limited effects and possibly only *single component failures* (e.g. El-Rashidy & Grant-Muller, 2014; Rupi et al., 2014; B. Chen et al., 2012; Azevedo et al., 2010; Jenelius et al., 2006). Disasters of the second category, on the other hand, are large-scale disruptive events (Jenelius & Mattsson, 2012) putting at stake critical infrastructure and causing *multiple component failures* (e.g. Yang et al., 2018; Dehghani et al., 2014; Nagae et al., 2012; Günneç & Salman, 2011; Al-Deek & Emam, 2006). In this context, single component failures can be viewed as the disaggregate level of multiple component failures. "Full range" studies, i.e. studies investigating all possible disruption scenarios, are until now limited to the assumption of single component failures (Jenelius & Mattsson, 2012). On the other hand, multiple component failures are treated as "scenario-specific" cases by either arbitrary assumptions or by means of Monte-Carlo simulation; this is due to the computational burden associated with the consideration of all possible disruption combinations, making such an attempt infeasible for large-scale networks.

2.3.2 Conceptual approach

Based on the disaster environment assumed, different approaches may be followed for the estimation of network performance. In addition, the literature investigates the use of a range of performance measures, while dependencies between components, the application of pre- and post-disaster interventions and the objectives set are additional parameters considered for that purpose.

2.3.2.1 Analysis type

Five analysis types can be identified for the estimation of network performance: *vulnerability*, *reliability*, *risk*, *robustness* and *resilience*. Terminology, however, is not consistent across the literature and the terms are often used under different conceptual contexts. As such, *vulnerability* is the most commonly used analysis type when investigating network sensitivity against disruptive events. When referring to a transportation network, it is many times associated with *accessibility*, the latter describing the ease of approaching a certain destination (Niemeier, 1997). As indicated by Berdica (2002), *accessibility* generally approaches the problem from a demand point of view whereas *serviceability* uses a supply approach, implying the existence of a functioning route to a destination and the possibility to use it. Accessibility is, therefore, highly related to *mobility* (Jones, 1981) and can, thus, provide misleading results regarding a network's physical state if strictly used in this context. In general, *vulnerability* refers to a network's susceptibility to incidents, which may lead to reduced serviceability (Berdica, 2002; A. Chen et al., 2007). For Burgholzer et al. (2012), vulnerability regards the reduction in network performance in the case of link disruptions, with Kermanshah & Derrible (2016) restricting its assessment to be made in quantitative terms, while for Johansson & Hassel (2010) vulnerability describes an incident's extent of impact. Jenelius et al. (2006) introduce two terms for interpreting vulnerability: "link importance" and "exposure". The first term incorporates the impact of link failures on costs and capacity, while the second term addresses low probability incidents and their impact on travelers. Later, Jenelius (2009) introduces "regional importance", "expected total exposure" and "expected user exposure", expanding his previously proposed terminology. In a later study, Jenelius & Mattsson (2015) define vulnerability as the societal risk of road infrastructure disruptions, with the concept of risk incorporating the scenario assumed, its probability of occurrence and the associated impact. Finally, Kurauchi et al. (2009), Taylor et al. (2006) and Taylor & Susilawati (2012), when considering vulnerability, focus on the impact of a failure instead of its occurrence probability.

Another term used to describe performance is *reliability*. In a transportation network, reliability can be defined as the possibility of successfully travelling between the nodes, taking, thus, into account both the likelihood of a disruption and its possible consequences (Berdica, 2002); in this term, "successfully" implies the satisfaction of certain evaluation criteria. For Soltani-Sobh et al. (2015), reliability refers to the probability that a network retains an acceptable level of service under unusual circumstances, while Nabian & Meidani (2018) restrain this to take place in a specified environment for a certain period of time. Reliability can generally be expressed in three main forms (Al-Deek & Emam, 2006; Berdica, 2002): (a) *connectivity reliability*, referring to the possibility of two network nodes remaining connected, (b) *travel time reliability*, referring to the possibility of reaching a certain destination within a time threshold, and (c) *capacity reliability*, referring to a network's ability to accommodate a certain amount of traffic. According to Jenelius et al. (2006), travel-time reliability depends on network performance expectations and is, thus, user-oriented, whereas connectivity reliability provides a more theoretical concept. However, since reliability is so probability-dependent, Kurauchi et al. (2009) point out that false probability estimations may well result in inaccurate reliability estimations. Taylor et al. (2006) and Taylor & D' Este (2007) illustrate the differences between vulnerability and reliability; they report that a network may be reliable, yet highly vulnerable at the same time, if the probability of failure is small but the associated impact is substantially high.

A concept closely related to reliability is that of *risk*. Risk is associated with the probability of a disruptive event and its associated impact (Berdica, 2002). In networks, risk is often defined as the combination of these two components (Jenelius et al., 2006). Taylor et al. (2006) and Taylor & D' Este (2007) note that, while vulnerability focuses on the impact, reliability and risk are more concerned with the probability of disaster occurrence and its consequences.

An opposing to vulnerability term is *robustness*, describing a network's strength (Knoop et al., 2012; Snelder et al., 2012). According to Sullivan et al. (2010), robustness is the degree to which a network can retain its performance when subjected to link capacity disruptions, while, in a similar framework, Zhang & Wang (2016) describe it as the ability to cope with extreme events and deliver a certain level of service. Kondo et al. (2012) associate robustness with connectivity reliability and accessibility. Knoop et al. (2012) consider robustness to be the network's ability to preserve its functionality under conditions that "deviate from the normal", while Snelder et al. (2012) describe robustness as "the extent to which, under pre-specified circumstances, a network is able to maintain the function for which it was originally designed". The latter argue that robustness is related to the impact of a disruption rather than its probability of occurrence and consider it in a framework of less frequent events of increased impacts.

Finally, *resilience* refers to a network’s ability to regain its normal function after a disruptive event (Omer et al., 2013; Berdica, 2002). Snelder et al. (2012) define resilience as a network's "temporary overload" and Barker et al. (2013) as a time-dependent proportional measure of a system's recovery over its loss. For Soltani-Sobh et al. (2015), this recovery should take place within a "reasonable" time frame. Miller-Hooks et al. (2012) and Zhang et al. (2015) indicate that resilience is not limited to the network’s ability to handle disruptions but also includes short-term, remedial actions for its restoration. Zobel & Khansa (2014) develop a measure for resilience in a multi-disaster environment; based on the work of Bruneau et al. (2003), Zobel (2010) and Zobel (2011), the authors extend the notion of single-disaster resilience to that of multi-disaster predicted resilience. Finally, Reggiani (2013) offers a framework for evaluating security resilience and argues that it should be examined in the context of weighted network topology / connectivity.

2.3.2.2 Dependencies

Since transportation networks are large-scale, spatially distributed systems, various forms of functional and spatial dependencies between their components and interdependencies with other systems are present (Little, 2002; Zimmerman, 2001); this fact implies that failures may cascade between both the network itself and the network and other lifelines (Johansson & Hassel, 2010). In this context, Rinaldi et al. (2001) distinguish *"dependencies"* (referring to components of the same network) from *"interdependencies"* (referring to different networks). Johansson & Hassel (2010) point out the need to specify whether the assumed interaction is treated on the macro (between systems) or on the micro (between system components) level and whether it has a bi- or a uni-directional form. In general, the inconsistency of terminology across the literature leads to the words "dependencies" and "interdependencies" being used interchangeably in some studies, while a difference in the nature of the interaction is indicated in others (Johansson & Hassel, 2010).

There exist several ways for the characterization of dependencies; Rinaldi et al. (2001) categorize them as physical (input-output dependence between components or systems), cyber (information transmission dependence), geographical (topological dependence between neighboring components affected by the same local event) and logical (all other dependence types). Zimmerman & Restrepo (2006) propose a broader categorization, where dependencies are viewed as either functional or spatial (the latter referring to geographical dependencies); the same categorization is adopted by Johansson & Hassel (2010) for modeling interdependencies in the case of infrastructure systems' vulnerability analysis.

With respect to transportation networks, a common assumption is that network components fail independently. Several researchers, however, discard this perception as being simplistic (Johansson & Hassel, 2010; Du & Nicholson, 1997). In real-world problems, not only components from the same network, but also infrastructures belonging to different networks, are interrelated, implying the existence of a possible relationship between their damage states as well. In this context, *cascading failures* refer to failures propagating within the same system due to flow redistribution, whereas *interdependent failures* refer to failures caused to a system as a result of failures to other systems (Hernandez-Fajardo & Dueñas-Osorio, 2013). Apart from that, a correlation between the damage states of facilities that does not fall into any of the aforementioned categories may also be observed; for example, Zhang & Wang (2016), Dong et al. (2014), Bocchini & Frangopol (2011) and Kiremidjian et al. (2007b) consider the effect of spatial correlation of earthquake ground motion on the observed bridge damage patterns and associate it with source-to-site distance, soil conditions and bridge characteristics. Bocchini & Frangopol (2011) point out that when performance-based design and assessment is pursued, the damage states of the individual components should be estimated, with the overall network performance resulting as a complex combination of them all. According to the same authors, the independence assumption between network components and their damage states can lead to significant errors in network performance estimation. However, the literature on the subject is still very limited (Günneç & Salman, 2011).

Overall, only a few papers consider some sort of functional or spatial dependency between network components and their failure states. In Miller-Hooks et al. (2012) this has the form of component correlation matrices while Du & Nicholson (1997) use arbitrary fraction values for the derivation of interrelated component arc capacities. Selçuk & Yücemen (1999) expand the notion of correlation to "spatially extending elements". More specifically, they partition each "element" into "components" and use two types of dependency models to calculate element reliability: the "point-site" model, where the element reliability equals that of the weakest component, and the "multi-site" model, where each element is treated as a series system and the upper and lower reliability values are derived through assumptions of independent and perfectly dependent components respectively. Pitilakis et al. (2006) account for four different types of interactions between lifeline systems while Johansson & Hassel (2010) use functional and geographical interdependencies between five infrastructure types to estimate the loss of service in a railway system. Günneç & Salman (2011) consider two forms of dependency: a set-based one, where components belonging to different sets fail independently, and a vulnerability-based one, where components of the same dependency set are ordered from the strongest to the weakest and failure of one component leads to failure of all the weaker ones. Finally, Du & Peeta (2014) derive link failure probabilities on the basis of the disaster's stochastic characteristics as well as possible pre-disaster link upgrading interventions.

2.3.2.3 Performance measures

Performance measures may generally be categorized as *flow-dependent* or *flow-independent*, with the former attempting to capture congestion phenomena, whilst the latter requires only data on the physical state of the network (Nojima, 1998). Chang & Nojima (2001) argue that flow-dependent measures are of limited practical significance in a post-disaster environment due to the lack of available data. Flow-independent measures, on the other hand, avoid the inherent stochasticity of flow estimations, focusing only on easier-to-estimate parameters.

In this context, Chang & Nojima (2001) use three different flow-independent measures: total length of network open and total and areal distance-based accessibility. Component length participates in all cases but under different concepts. The first measure describes the fraction of failure-free network length, irrespective of the open segments' allocation and connectivity. In the second case, initial component length, damage state and connectivity are combined to provide a minimum distance path estimate of origin - destination (OD) pair accessibility, with nodal weighting factors according to pre-disaster OD data incorporated in the final measure. In a different approach, Ukkusuri & Yushimito (2009) decline the use of shortest distance paths for performance estimation; in their study, criticality of network links is assessed by link capacity reductions and user equilibrium (UE) analysis, with performance measured as the sum of all arcs' travel times. It is, thus, obvious that even the same parameter (e.g. component length) when used under different frameworks can result in different performance estimates.

Another important observation is that performance measures are not necessarily dictated by the type of analysis followed. For example, when network connectivity is investigated, reliability analysis, focusing on component survival probabilities, could be employed. This approach was followed by Selçuk & Yücemen (1999), with component probabilities calculated on the basis of their strength and the seismic loading they were subjected to. Similarly, Peeta et al. (2010) combine connectivity reliability with generalized travel cost in a two-stage stochastic program aiming at strengthening a highway network. Connectivity, however, has also been used in a vulnerability analysis context; far from probability estimations, Kurauchi et al. (2009) examine OD-connectivity from a topological point of view, defining it as the number of disjoint paths between each OD pair under link disruption scenarios, with path selection based on acceptable travel time thresholds.

Indices describing network performance can be further categorized as time-, distance- and cost-based. Time-based measures include *travel time* and *travel time increases*, on the network (e.g. Edrisi & Askari, 2019; Guo et al., 2017; Jenelius & Mattsson, 2015; Yang & Qian, 2012; Ukkusuri & Yushimito, 2009; Kiremidjian et al., 2007b) and on specific parts of it (link-, path, OD-based etc.) (e.g. Donovan & Work, 2015; Omer et al., 2013; Burgholzer et al., 2012), *out-of-service time* (e.g. Dong et al., 2014; Augusti & Ciampoli, 1998) etc. Distance-based measures include *total length of network open* (e.g. Chang & Nojima, 2001), *total length of network affected or exposed to hazard* (e.g. Kermanshah & Derrible, 2016; Cirianni et al., 2012), *shortest distance paths between the OD-pairs* (e.g. Yang et al., 2018; Dehghani et al., 2014; Günneç & Salman, 2011) etc. Cost-based measures include *generalized travel cost*, i.e. any proper measure estimating travel impedance (e.g. time, distance, cost) (e.g. Taylor et al., 2006), *repair* (e.g. Liu et al., 2009) and *anti-seismic reinforcement cost* (e.g. Nagae et al., 2012) etc. Other performance indices such as *network connectivity*, i.e. the extent to which network nodes remain connected (e.g. Nabian & Meidani, 2018; Hu et al., 2016; Zhang & Wang, 2016; Bono & Gutiérrez, 2011; Peeta et al., 2010), *damage level* (e.g. Bocchini & Frangopol, 2011; Azevedo et al., 2010) and *demand / flow measures* (e.g. Li et al., 2019a; Di et al., 2018; Rupi et al., 2014; Jenelius & Mattsson, 2012; Johansson & Hassel, 2010; Matisziw & Murray, 2009; Nojima, 1998) are also encountered in literature.

2.3.2.4 Pre- and post-disaster interventions

Evaluation of the network's strengths and weaknesses is important in allowing for efficient preparation against disruptive events. However, the identification of the network's critical links or the assessment of the disruption impact will only result in a ranking of intervention priorities and a list of possible consequences unless it is accompanied by an actual resource allocation in either the pre- or post-disaster stages. This takes the form of mitigation interventions in the first case (e.g. Edrisi & Askari, 2019; Kumar et al., 2019; Wang & Jia, 2019; Xu et al., 2018; Yang et al., 2018; Zhang & Wang, 2016; Edrissi et al., 2015; Du & Peeta, 2014; Edrissi et al., 2013; Nagae et al., 2012; Peeta et al., 2010), or of restoration decisions in the second one (e.g. Li et al., 2019a; Nabian & Meidani, 2018; Zhang et al., 2017; Dong et al, 2014; Vugrin et al., 2014; Karlaftis et al., 2007), with some papers considering both (e.g. Zhang et al., 2015; Faturechi & Miller-Hooks, 2014; Miller-Hooks et al., 2012); either way, the scope lies in the enhancement of network performance. Most papers dealing with restoration or reinforcement strategies consider bridge networks only; according to Peeta et al. (2010), bridges are the most damage-susceptible part of the network, whose restoration is both time-consuming and capital-intensive. In addition, parameters considered in the problem formulation may vary. In Karlaftis et al. (2007) post-disaster fund allocation is based on bridge importance ratings and condition improvement, Liu et al. (2009) aim at minimizing the cost of repair and travel time delays, while Augusti et al. (1994) account for the structural fragility of different types of bridges and for network's connectivity reliability.

2.3.2.5 Objectives

Common objective of network performance studies is the identification of the network's *critical links* (e.g. Yang et al., 2018; Soltani-Sobh et al., 2015; Balijepalli & Oppong, 2014; El-Rashidy & Grant-Muller, 2014; Rupi et al, 2014; Barker et al., 2013; B. Chen et al., 2012; Yang & Qian, 2012; Sullivan et al., 2010). Although different criteria may be used, Taylor & Susilawati (2012) point out that the impact assessment of failures crosscuts all studies, irrespective of the actual performance measure used. In cases of pre- or post-disaster interventions, the focus lies on the *prioritization of the facilities to be repaired or reinforced* (e.g. Kumar et al., 2019; Li et al., 2019a; Nabian & Meidani, 2018; Zhang et al., 2017; Hu et al., 2016; Tuzun Aksu & Ozdamar, 2014) and the respective *budget allocation* (e.g. Zhang & Wang, 2016; Edrissi et al., 2015; Zhang et al., 2015; Du & Peeta, 2014; Faturechi & Miller-Hooks, 2014; Vugrin et al, 2014; Edrissi et al., 2013; Nagae et al., 2012; Liu et al., 2009; Karlaftis et al., 2007). Under the framework adopted in each study and with respect to the type of analysis considered, several other objectives may be identified; these may vary from the identification of the network's vulnerability disparities (e.g. Jenelius & Mattsson, 2012), to the estimation of the network's robustness using topological attributes and the opportunities present at each node (e.g. Kondo et al., 2012), the assessment of flood risk and its impact on vehicle speed (e.g. Pregnolato et al., 2017) etc.

Table 2.1 Classification of network performance studies with respect to analysis type and failure representation

Component failure extent	Type of Analysis: Vulnerability	Robustness	Resilience	Reliability	Risk
Complete	Kermanshah & Derrible (2016), Jenelius & Mattsson (2015), Dehghani et al. (2014), El-Rashidy & Grant-Muller (2014), Rupi et al. (2014), Tuzun Aksu & Ozdamar (2014), B. Chen et al. (2012), Jenelius & Mattsson (2012), Knoop et al. (2012), Nagae et al. (2012), Taylor & Susilawati (2012), Yang & Qian (2012), Bono & Gutiérrez (2011), Johansson & Hassel (2010) (*), Jenelius (2009), Kurauchi et al. (2009), Matisziw & Murray (2009), Ukkusuri & Yushimito (2009), Qiang & Nagurney (2008), Taylor & D' Este (2007), Jenelius et al. (2006), Sohn (2006), Taylor et al. (2006)	Kondo et al. (2012)	Edrisi & Askari (2019), Yang et al. (2018), Ganin et al. (2017), Hu et al. (2016), Zhang & Wang (2016) (*), Du & Peeta (2014) (*), Faturechi & Miller-Hooks (2014)	Nabian & Meidani (2018), Edrissi et al. (2015), Edrissi et al. (2013), Günneç & Salman (2011) (*), Peeta et al. (2010), Poorzahedy & Bushehri (2005), Nojima & Sugito (2000), Selçuk & Yücemen (1999) (*), Augusti & Ciampoli (1998), Nojima (1998), Augusti et al. (1994)	Liu et al. (2009)
Partial	Guo et al. (2017), Balijepalli & Oppong (2014), Dong et al. (2014), Burgholzer et al. (2012), Bocchini & Frangopol (2011) (*), Azevedo et al. (2010), A. Chen et al. (2007), Karlaftis et al. (2007), Chang (2003), Chang & Nojima (2001), Nicholson & Du (1997)	Snelder et al. (2012), Sullivan et al. (2010), Nagurney & Qiang (2009)	Li et al. (2019a), Zhang et al. (2017), Zhang et al. (2015), Vugrin et al. (2014), Omer et al. (2013), Barker et al. (2013), Miller-Hooks et al. (2012) (*)	Wang & Jia (2019), Soltani-Sobh et al. (2016), Soltani-Sobh et al. (2015), Chen et al. (2013), Al-Deek & Emam (2006), Du & Nicholson (1997) (*)	Pregnolato et al. (2017), Kiremidjian et al. (2007a), Kiremidjian et al. (2007b) (*), Pitilakis et al. (2006) (*)
Without	Kumar et al. (2019), Di et al. (2018), Chen & Li (2017), Khademi et al. (2015), Yang et al. (2013)	Sakakibara et al. (2004)	Xu et al. (2018), Donovan & Work (2015), Reggiani (2013), Tamvakis & Xenidis (2012)		Cirianni et al. (2012)

(*) consideration of some sort of dependency between the network components and their failure states

Table 2.2 Classification of the network performance studies with respect to the performance measures used

	Performance measures					
	Connectivity	Accessibility	TNTT (or increase)*	TT (or increase)**	Demand / flow	Other
Edrisi & Askari (2019)			*			*
Kumar et al. (2019)			*		*	*
Li et al. (2019a)					*	*
Wang & Jia (2019)			*			
Di et al. (2018)		*			*	
Nabian & Meidani (2018)	*					
Xu et al. (2018)	*				*	
Yang et al. (2018)	*		*			*
Chen & Li (2017)					*	
Ganin et al. (2017)						*
Guo et al. (2017)	*		*			*
Pregnolato et al. (2017)	*					*
Zhang et al. (2017)	*					*
Hu et al. (2016)	*					
Kermanshah & Derrible (2016)		*			*	*
Soltani-Sobh et al. (2016)					*	
Zhang & Wang (2016)	*					*
Donovan & Work (2015)				*		*
Edrissi et al. (2015)						*
Jenelius & Mattsson (2015)			*	*	*	
Khademi et al. (2015)	*					*
Soltani-Sobh et al. (2015)			*		*	*
Zhang et al. (2015)	*				*	*
Balijepalli & Oppong (2014)			*		*	*
Dehghani et al. (2014)	*					*
Dong et al. (2014)						*
Du & Peeta (2014)	*		*			*
El-Rashidy & Grant-Muller (2014)			*		*	*
Faturechi & Miller-Hooks (2014)			*			
Rupi et al. (2014)			*		*	
Tuzun Aksu & Ozdamar (2014)		*				
Vugrin et al. (2014)			*		*	
Barker et al. (2013)					*	
Chen et al. (2013)					*	
Edrissi et al. (2013)						*
Omer et al. (2013)				*		*
Yang et al. (2013)	*				*	*
Reggiani (2013)	*					
Burgholzer et al. (2012)			*	*		*
B. Chen et al. (2012)				*		*
Cirianni et al. (2012)						*
Jenelius & Mattsson (2012)			*	*	*	
Knoop et al. (2012)				*		*
Kondo et al. (2012)	*	*				
Miller-Hooks et al. (2012)					*	
Nagae et al. (2012)						*
Snelder et al. (2012)				*		
Tamvakis & Xenidis (2012)						*
Taylor & Susilawati (2012)		*				
Yang & Qian (2012)			*			

	Performance measures					
	Connectivity	Accessibility	TNTT (or increase)*	TT (or increase)**	Demand / flow	Other
Bocchini & Frangopol (2011)	*		*			*
Bono & Gutierrez (2011)	*	*				
Günneç & Salman (2011)	*					*
Azevedo et al. (2010)	*					*
Johansson & Hassel (2010)					*	*
Peeta et al. (2010)	*					*
Sullivan et al. (2010)			*			*
Jenelius (2009)			*	*		
Kurauchi et al. (2009)	*		*			
Liu et al. (2009)			*			*
Matisziw & Murray (2009)	*				*	
Nagurney & Qiang (2009)			*			
Ukkusuri & Yushimito (2009)			*			
Qiang & Nagurney (2008)						*
A. Chen et al. (2007)		*				
Karlaftis et al. (2007)						*
Kiremidjian et al. (2007a)				*		
Kiremidjian et al. (2007b)			*			
Taylor & D' Este (2007)		*	*	*		
Al-Deek & Emam (2006)				*		*
Jenelius et al. (2006)			*	*	*	*
Pitilakis et al. (2006)	*					
Sohn (2006)		*				
Taylor et al. (2006)		*	*	*		
Poorzahedy & Bushehri (2005)						*
Sakakibara et al. (2004)	*					
Chang (2003)		*				
Chang & Nojima (2001)		*				*
Nojima & Sugito (2000)	*					*
Selçuk & Yücemen (1999)	*					
Augusti & Ciampoli (1998)	*					*
Nojima (1998)	*				*	
Du & Nicholson (1997)						*
Nicholson & Du (1997)						*
Augusti et al. (1994)	*					

* TNTT: Total Network Travel Time

** TT: Travel Time (link-, path-, OD-based etc.)

2.4 Network operations' planning

The approaches used for the conceptualization, modeling and estimation of network performance set the basis for the decision-making and planning of post-disaster *operations*. Despite the abundance of existing possibilities, two specific operation types, namely *evacuation* and *emergency traffic management*, are considered. Each operation comprises a set of *actions* and is realized through a set of *strategies*. Classification of the associated literature is based on the framework of **Figure 2.3** and includes (a) the planning scope, and (b) the planning process adopted. The first term refers to the type of operations employed as well as to their planning and implementation timing. The second term focuses on the actual decision-making process and comprises the actions determined, the analysis tools used, the strategies and parameters identified and the objectives set. In this context, **Table 2.3** enumerates the possible operations in the pre- and post-disaster phases, **Table 2.4** categorizes research studies with respect to their planning timing, the actions undertaken and the analysis tools employed, while **Table 2.5** lists the strategies and parameters assumed in each case.

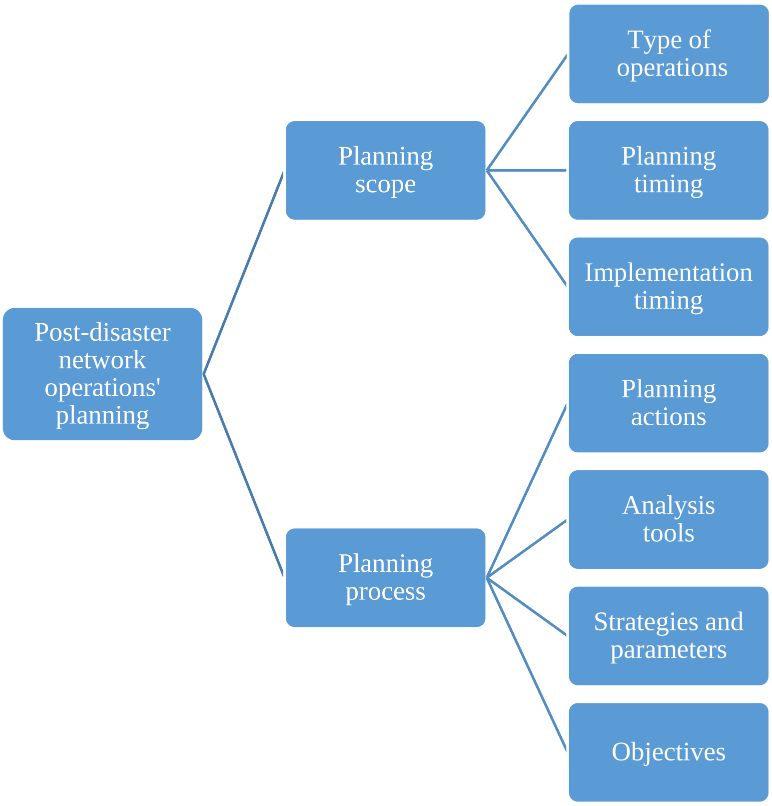


Figure 2.3 Classification framework for post-disaster network operations' planning

2.4.1 Planning scope

In this category, emphasis is placed on the type of operations considered and the associated planning and implementation timing assumed. The outcome is the formulation of the generalized post-disaster network management framework.

2.4.1.1 Type of operations

Two types of operations are considered: *evacuation* and *emergency traffic management*. *Evacuation* has been widely investigated in the literature (e.g. Lu et al. (2020); Karabuk &

Manzour, 2019; He et al., 2018; Li et al., 2018; Moshtagh et al., 2018; Henry et al., 2017; Kim et al., 2017; Yuan et al., 2017; Marcianò et al., 2015; Goerigk et al., 2014). It can be identified as a non "orderly" process, which involves uncertainties pertaining to the incident itself as well as to demand, supply and operational issues (Barrett et al., 2000). Typically, most evacuation studies assume single direction of movement; traffic is only heading outbound, from harm to safety zones, with no capacity reserved for inbound traffic. *Emergency traffic management* on the other hand considers bi-directional traffic movement and aims at preserving network functionality by considering the needs generated by all network users (Iida et al., 2000). Studies in the field, however, are still scarce (e.g. Sumalee & Kurauchi, 2006; Feng & Wen, 2005, 2003; Iida et al., 2000).

2.4.1.2 Planning timing

Planning in a disaster management context generally entails the modeling of a network, its operations and performance under increased demand and possibly reduced capacity (Balakrishna et al., 2008); this process may precede or succeed a disaster. In Zimmerman et al. (2007), *preplanning* refers to activities taking place before an incident occurs, whereas *advance planning* is based on a priori, incident-specific information with frequent use of preplanning data. Preplanning becomes increasingly important in the case of no-notice disasters, where it may make up for the limited or non-existing readiness phase and the associated advance planning (Zimmerman et al., 2007). As such, preplanning constitutes the pro-active part of disaster management, taking the form of strategic plans referring to any of the pre-, during and post-disaster phases (e.g. Karabuk & Manzour, 2019; Li et al., 2018; Üster et al., 2018; Kim et al., 2017; Gan et al., 2016; Bayram et al., 2015; Li & Ozbay, 2015; Goerigk et al., 2014; Hu et al., 2013; Nakanishi et al., 2013).

On the contrary, advance planning belongs to the disaster management's re-active part and is related to *real-time management*. The latter aspires to provide improved network performance and reduced losses in the case of emergencies (Liu et al., 2007); its contribution is justified by the dynamic and stochastic nature of disasters as well as by the complexity of traffic flow modeling which cannot be captured in the preplanning process (Liu et al., 2007; Chiu & Mirchandani, 2008). In this context, Liu et al. (2007) and Chiu & Mirchandani (2008) agree that real-time management must be "traffic adaptive", implying the necessity for the re-adjustment of strategies on the basis of the prevailing traffic conditions. Despite being promising, though, real-time management poses operational difficulties due to its excessive information, resource, personnel and co-ordination needs between the agencies. Thus, studies attempting an integrated approach of planning with real-time management are limited (e.g. Daganzo & So, 2011; Balakrishna et al., 2008; Chiu & Mirchandani, 2008; Hamza-Lup et al., 2008; Liu et al., 2007; Pal et al., 2003), with Barrett et al. (2000) and Tufekci (1995) proposing theoretical frameworks for hurricane evacuation, Min & Lee (2013) developing real-time contraflow evacuation schemes for maximum throughput flows, Ukkusuri et al. (2017) allowing for en-route route choice adaptations etc.

2.4.1.3 Implementation timing

Three main phases may be distinguished with respect to the time evolution of the phenomenon: the pre-, during, and post-disaster phases. However, since the duration of the phenomenon can often be considered negligible when compared to the extent of the time preceding or succeeding it, the latter two phases are often merged into one. In addition, the different characteristics exhibited by each phase call for the deployment of distinct operations. A respective categorization is made in **Table 2.3**.

Table 2.3 Operations undertaken in the pre- and post-disaster phases

Type of operations	Pre-disaster phase	Post-disaster phase
Infrastructure inspection	*	*
Network performance enhancement interventions	*	*
Critical infrastructure location (hospitals, fire-stations, shelters, warehouses etc)	*	
Districting	*	
Emergency plans formulation	*	*
Emergency response (EVs location / allocation / dispatching / routing)		*
Evacuation	*	*
Emergency logistics		*
Traffic management & control	*	*
Social media – information technology	*	*

Galindo & Batta (2013) identify four operational stages in disaster management: mitigation, preparedness, response and recovery. *Mitigation* refers to the actions undertaken to prevent a disaster or lessen its impact, while *preparedness* includes community preparation to ensure its best possible response; both stages belong to the pre-disaster phase. *Response* refers to the operations assumed during and shortly after a disaster to accommodate the diverse needs arising. Finally, *recovery* aims at community restoration and is part of the post-disaster phase. In an evacuation context, Zimmerman et al. (2007) describe the above stages with a slightly different terminology, referring to planning and preparedness, readiness, activation, operations and return-to-readiness. *Planning and preparedness* coincides with the aforementioned stages of mitigation and preparedness. During the *readiness phase*, stakeholders use the available information to decide upon the need (or not) to evacuate a region and the way this is going to be accomplished; in no-notice disasters the limited or absent readiness phase raises the importance of *preplanning* operations. The *activation phase* includes the preliminary steps for the evacuation, while during the *operations phase*, the actual evacuation operation as well as the re-entry of the evacuees take place. Finally, in the *return-to-readiness phase*, lessons learned from the incident are exploited for handling future catastrophes.

2.4.2 Planning process

This category pertains to details regarding the decision making process; parameters reviewed include the actions undertaken as part of the operations considered, the analysis tools exploited, the strategies and parameters assumed and the planning objectives set.

2.4.2.1 Planning actions

Action types refer to the specific tasks undertaken as part of the general operations. Most papers investigate *traffic routing,* i.e. the identification of efficient routes for different types of service provision (e.g. Fahad et al., 2019; Shahabi & Wilson, 2018, 2014; Henry et al., 2017; Wang et al., 2017, 2013; Min & Lee, 2013). Route identification may vary on the basis of the objectives pursued, the restrictions imposed and the parameters assumed; for example, optimal routes may differ on the basis of distance or travel time minimization or when a specific respective threshold is supposed. Routes may also differ with respect to distinct operation types; for example, emergency response and evacuation will inevitably have routes of opposing direction. In addition, route establishment in the post-disaster phase is directly related to the occurrence of network component failures and needs to be dynamically altered according to traffic-related feedback (Chiu et al., 2007).

Furthermore, during evacuation, the timely and effective transportation of citizens to safety requires satisfactory utilization of the transportation network; the latter is achieved through either capacity augmentation or demand spreading (Pillac et al., 2016; Sbayti & Mahmassani, 2006). Afshar & Haghani (2008) note that, in cases of simultaneous evacuation, the sudden surge of traffic may quickly overwhelm the network and lead to congestion phenomena with devastating consequences. Sadri et al. (2013) and Chiu & Mirchandani (2008) also highlight the fact; synchronized evacuation behaviors (departure time and route choice) may bring the transportation network to a stall. On the other hand, a staged evacuation, i.e. an evacuation where evacuees are advised on when to evacuate and which route to choose, can better exploit network potential and prevent congestion (Li et al., 2015; Afshar & Haghani, 2008). This type of action, where a time component is additionally involved in the routing process, is denoted as *traffic routing and scheduling* (e.g. Karabuk & Manzour, 2019; Li et al., 2018; Gan et al., 2016; Pillac et al., 2016, 2015; Li & Ozbay, 2015; Bish et al., 2014).

Attention must also be paid to *evacuation demand estimation,* as trip generation is the first and most crucial step in transportation modeling, yet the least explored (Wilmot & Mei, 2004). This may be attributed to the lack of available data, concerns about their accuracy and doubts regarding the applicability of a certain model to a region or disaster type other than the one it was made for (Li et al., 2013). Indeed, behavioral aspects pertaining to both evacuation decision and route choice have mostly been studied from a qualitative, as opposed to a quantitative, standpoint (Hsu & Peeta, 2013; Chiu & Mirchandani, 2008). As such, indicative studies in the field that attempt a quantitative approach include those of Gudishala & Wilmot (2013), Li et al. (2013) and Wilmot & Mei (2004), while more information on evacuation decision, as this is revealed through stated preference (SP) and revealed preference (RP) surveys, can be found in Thompson et al. (2017).

Finally, other types of actions may refer to the formulation of traffic signal timing plans (e.g. Marcianò et al., 2015; Hamza-Lup et al., 2008; M. Chen et al., 2007; Liu et al., 2007) or evacuation warning zones to facilitate warning timing and evacuation staging (e.g. Li et al., 2015), the estimation of traffic safety hazards (e.g. Tu et al., 2013), the planning of urban re-construction (land use) and travel demand during the recovery phase (e.g. Nakanishi et al., 2013), the exploration of the effect of physical, biological and social parameters on evacuation (e.g. Brachman & Dragicevic, 2014), the optimization of ride-sharing matching with transfers during short-notice evacuations (e.g. Lu et al., 2020) etc. Papers in this category may also comprise a combination of actions, such as the location of shelters and the routing of private cars in Bayram et al. (2015) and additionally transit vehicles in Goerigk et al. (2014), the joint analysis of evacuation demand estimation and route selection under behaviorally-consistent information provision in Hsu & Peeta (2013) with additional determination of evacuation risk zones in Hsu & Peeta (2014a), the integration of behavioral models for household-level hurricane evacuation decision-making (evacuation decision, departure timing, mode and destination) with traffic simulation (en-route route choice) in Ukkusuri et al. (2017), the strategic design of evacuation networks with appropriate selection of shelters and routes and determination of possible capacity enhancements under budgetary constraints in Üster et al. (2018) etc.

2.4.2.2 Analysis tools

Operations involving a routing component can be modeled through either an optimization- or a simulation-based approach (Xie et al., 2010). An *optimization-based* model typically uses network flow and routing algorithms to achieve certain performance objectives (Xie et al., 2010). Both *dynamic* and *static* formulations may be developed, with the first ones being more realistic (Kotnyek, 2003). Differentiation lies in the introduction of time, since dynamic problems involve at least one variable which is "a function of time" (Kotnyek, 2003). In this context, static traffic assignment uses steady-state traffic information (Chiu & Mirchandani, 2008), whereas dynamic traffic assignment works with time-varying flows in order to provide a realistic representation of traffic conditions (Peeta & Ziliaskopoulos, 2001). In addition, dynamic network flow problems comprise a wider range of formulations compared to their static counterparts (Kotnyek, 2003). Mahmassani (2001) considers static network flow problems to be appropriate for long-term transportation planning, while dynamic ones are suitable for real-time operations. He stresses, though, that satisfactory representation of flow propagation in dynamic models can yield problems in solution tractability, as analytical solutions are generally impossible to reach (Mahmassani, 2001).

Simulation, on the other hand, "involves replication of real world transportation system operations through mathematical and logical representations of interactions of the entities present in the system" (Sisiopiku, 2007). Simulation is generally case-specific and offers improved analysis capabilities (ITE – California Border Section, 2004). Depending on the level of detail, researchers have exploited *macroscopic* (e.g. Hobeika & Kim, 1998), *mesoscopic* (e.g. Hsu & Peeta, 2014a, 2014b, 2013; Fang & Edara, 2013; Xie et al., 2010; Afshar & Haghani, 2008; Chiu & Mirchandani, 2008) and *microscopic* (e.g. Fahad et al., 2019; Kim et al., 2017; Ukkusuri et al., 2017; Yuan et al., 2017; Zhang et al., 2014; Tu et al., 2013; Lämmel et al., 2010; Jha et al., 2004) simulation models. *Microscopic* models are the most detailed of all, as they capture the characteristics of each individual vehicle and its movement across the network (Pidd et al., 1996). Most of them belong to the class of car-following, lane-changing and gap acceptance models (Barcelo et al., 2004). On the contrary, *macroscopic* models simulate traffic flow based on general traffic characteristics like speed and density. Equations used to describe these variables are similar to the ones describing flows in fluids (Helbing, 1998; Pidd et al., 1996). Finally, *mesoscopic* models bridge the gap between the two categories by simulating individual vehicles (as in microscopic models), but ascribing them aggregate attributes (as in macroscopic models) (Montz & Zhang, 2013).

Simulation is generally more time-intensive compared to the optimization-based approaches and is therefore deemed to not be appropriate for large-scale networks (Xie et al., 2010); as such, operations' planning is mostly based on the latter (e.g. Lu et al., 2020; Karabuk & Manzour, 2019; He et al., 2018; Li et al., 2018; Bayram et al., 2015; Li & Ozbay, 2015; Pillac et al., 2015; Goerigk et al., 2014; Bish & Sherali, 2013; Luo et al., 2013; Campos et al., 2012; Takizawa et al., 2011). Xie et al. (2010) also argue that simulation plays more a "what if" experiment role, whereas optimization approaches work on a "what to do" basis. This implies that simulation could be used to check the adequacy of already formulated emergency plans whereas optimization would be used as a tool to develop them.

2.4.2.3 Strategies and parameters

The operations' planning phase allows for a range of possible strategies to be employed and parameters to be assumed; in this context, *network management strategies* refer to the actions considered to be the problem’s decision variables. These may include roadway capacity changes (lane reversal / contraflow, use of shoulder lanes), intersection modeling (crossing conflicts prohibition, merging conflicts limitation, traffic signal timing plans formulation), specification of evacuation priorities and regulation of demand.

Lane-based strategies aim at increasing roadway capacity along the most heavily congested direction, while promoting traffic safety. *Contraflow*, in particular, refers to shifting the direction of all opposing lanes on a roadway segment (e.g. He et al., 2018; Kostovasili & Antoniou, 2017; Pyakurel & Dhamala, 2017; Pillac et al., 2016), while *lane reversal* reserves some capacity for the inbound traffic, consisting of emergency vehicles, rescue crews but also civilians (e.g. Xie & Turnquist, 2011; Xie et al., 2010; M. Chen et al., 2007); the distinction, however, is not always clear and the terms are also used interchangeably. Contraflow has been implemented by many States across the US and has proved to be successful in reducing evacuation times (Xie & Turnquist, 2011; Houston, 2006). In addition, *shoulder lanes*, i.e. the side lanes along highways used by emergency vehicles, can be effectively incorporated into the main traffic stream to augment the capacity and facilitate the flows (e.g. Üster et al., 2018; Liu et al., 2006; Hobeika & Kim, 1998).

Intersection modeling constitutes another category of management strategies. Turning intersections into *un-interrupted flow facilities (crossing conflicts prohibition)* (e.g. Luo et al., 2013; Bretschneider & Kimms, 2011) removes possible stopping delays at them and has the potential of reducing the total evacuation time (Hua et al., 2013; Xie & Turnquist, 2011; Cova & Johnson, 2003). It also restricts the number of alternative evacuation routes, providing, thus, a more easily comprehensible and manageable evacuation network (Hua et al., 2013; Xie et al., 2010). *Merging conflicts limitation* (e.g. Hua et al., 2013; Bretschneider & Kimms, 2012) can further reduce intersection delays, while both strategies decrease the potential intersection accident points (Hua et al., 2013; Xie et al., 2010; Cova & Johnson, 2003). *Traffic signal timing* *plans formulation* is another area of interest. M. Chen et al. (2007) pay explicit attention to the subject, while other approaches include those of: (a) Li et al. (2006), who adopt a pre-defined, long signal cycle for the evacuation routes, (b) Hamza-Lup et al. (2008), who use pre-timed and actuated signals, (c) Wei et al. (2008), who combine signal timing with access control, (d) Chen & Xiao (2008), who additionally account for the parking rate in their signal timing model, and (e) Marcianò et al. (2015), who construct signal timing plans while considering traffic dynamics and path choice behavior.

Designation of evacuation priorities serves the scope of life protection. Two forms may be distinguished in the literature: (a) prioritization of whole regions on the basis of the risk level they experience (e.g. Hsu & Peeta, 2014a, 2014b; Bish & Sherali, 2013; Lim et al., 2012; Daganzo & So, 2011; Lahmar et al., 2006), and (b) prioritization of evacuation routes and / or heavily congested road sections, with emphasis placed on the amount of flow present (e.g. Wei et al., 2008; Sinuany-Stern & Stern, 1993). Thus, in the first case, priority is given to the population most-at-risk while, in the second case, to the highest demand. Composite priority measures have also been developed (e.g. Nassir et al., 2014, 2013; Kimms & Maassen, 2011), along with the designation of evacuation priorities on the basis of evacuees' categorization (for example, depending on their level of injury) (e.g. Dulebenets et al., 2019; Karabuk & Manzour, 2019; Wang et al., 2013) or of their proximity to specified evacuation exit points (e.g. Tu et al., 2013).

Finally, *demand regulation* generally refers to imposing some kind of control over the allowable traffic movements. This may take different forms and regard the percentage of traffic allowed to enter disaster-raided regions (e.g. Feng & Wen, 2005, 2003; Iida et al., 2000), travel between OD pairs (e.g. Sumalee & Kurauchi, 2006), or enter specific roadway segments, such as highways (e.g. Daganzo & So, 2011; Sisiopiku, 2007). Indeed, highways may operate under an access control policy in the aftermath of a disaster, in order to prevent network overloading resulting in gridlocks and excessive travel time delays. Along with local traffic diversion, access restrictions can help ensure that traffic on the main evacuation routes will be given priority (also according to the previously mentioned management strategy).

Several other *parameters* pertain to the problem formulation. Behavioral characteristics, such as the possibility of arbitrary (shadow) evacuation or evacuees' non-compliance to orders and recommendations are listed by Zimmerman et al. (2007) as potential problems hindering evacuation effectiveness. More specifically, shadow evacuation can potentially overwhelm network capacity, thus, making it more difficult for actual evacuees to reach safety (Lamb et al., 2012). In addition, the optimality of the management strategies implemented severely deteriorates under the assumption of partial evacuee compliance (Fu et al., 2013). Research on the subject includes the work of Henry et al. (2017), Bish et al. (2014), Hsu & Peeta (2014a, 2014b, 2013), Fu et al. (2013), Lambert et al. (2013), Sadri et al. (2013) and Lin et al. (2009), while more information on the behavioral aspects of evacuation may be found in Iliopoulou et al. (2019). Route choice is another parameter, which remains relatively unexplored. As X. Chen et al. (2012) note, most papers focus on developing optimal routing strategies, but fail to account for the individuals' perception of risk and how this interferes with their decisions. A different than optimal routing option was examined by Ukkusuri et al. (2017), Yuan et al. (2017), Hsu &

Peeta (2014a, 2014b, 2013), Fang & Edara (2013), Sadri et al. (2013), X. Chen et al. (2012), Chiu & Mirchandani (2008), Sumalee & Kurauchi (2006) and Sinuany-Stern & Stern (1993), with the subject extensively investigated in **Section 3.4**. In addition, some studies consider evacuation demand to spread over time, resulting in a gradual, as opposed to direct, network loading. In such cases, evacuees' departure times are assumed to follow response or mobilization curves, including the sigmoid curve or curves adopted from various probability distributions (Rayleigh, Weibull, exponential etc.) (Bayram, 2016). The assumption of a staged evacuation was adopted by Gan et al. (2016), Goerigk et al. (2014), Pillac et al. (2015), Fu et al. (2013) etc. Other problem aspects, such as the consideration of network component failures (e.g. Fahad et al., 2019; Pillac et al., 2016, 2015; Brachman & Dragicevic, 2014; Sumalee & Kurauchi, 2006) or of background traffic (e.g. Marcianò et al., 2015; Hsu & Peeta, 2014a, 2013; Lambert et al., 2013) are also included in this category. Infrastructure failures are critical when planning operations due to the possibility of rendering some of the initially designed routes inoperable. Furthermore, background traffic, i.e. traffic already present on the network at the time when the evacuation order is issued, must be appropriately modeled to ensure an accurate representation of the initial network conditions (Jha et al., 2004). Finally, constraints incorporated in problem formulation usually include those of link capacity (practically all studies), shelter capacity (e.g. He et al., 2018; Yuan et al., 2017; Bayram et al., 2015; Goerigk et al., 2014; Hu et al., 2013) and distance from shelter (e.g. Yuan et al., 2017; Bayram et al., 2015; Saadatseresht et al., 2009).

2.4.2.4 Objectives

Multiple emergency planning objectives can be specified in the literature. Most studies aim at minimizing some performance measure, including *network clearance time*, i.e. the time corresponding to the last vehicle / evacuee leaving the impact area (e.g. Li et al., 2019b; Henry et al., 2017; Yuan et al., 2017; Li & Ozbay, 2015; Goerigk et al., 2014; Bish & Sherali, 2013; Kalafatas & Peeta, 2009; Balakrishna et al., 2008), *total evacuation time* (e.g. Shahabi & Wilson, 2018, 2014; Gan et al., 2016; Wang et al., 2016; Bayram et al., 2015; Bretschneider & Kimms, 2012; Xie & Turnquist, 2011; Ng & Waller, 2010) or *total network travel time*, i.e. the sum of all vehicles' travel times (e.g. Dulebenets et al., 2019; He et al., 2018; Lin et al., 2009; Chiu et al., 2007; Liu et al., 2007), *total travel distance* (e.g. Nakanishi et al., 2013; Stepanov & MacGregor Smith, 2009; Cova & Johnson, 2003), *evacuees' total threat exposure*, as indicated by exposure duration and severity (e.g. Nassir et al., 2014, 2013), *total cost* expressed in monetary values (e.g. Üster et al., 2018; Hu et al., 2013) or in a more generic form (e.g. Lu et al., 2020; Brachman & Dragicevic, 2014; An et al., 2013; Duanmu et al., 2012) and so on. Other studies pursue the maximization of the *total number of evacuees* reaching safety (e.g. Kostovasili & Antoniou, 2017; Pillac et al., 2016, 2015; Lv et al., 2013; Lim et al., 2012; Takizawa et al., 2011; Zhou & Liu, 2011) or explore the *effect of different route-choice behaviors* on performance measures such as the average evacuee travel time (e.g. Fang & Edara, 2013), the total network travel time (e.g. Chiu & Mirchandani, 2008), the total evacuation time (e.g. Hsu & Peeta, 2014a) or the network clearance time (e.g. Hsu & Peeta, 2014b), while many studies pursue the optimization of more than one objective (e.g. Lu et al., 2020; Karabuk & Manzour, 2019; Li et al., 2018; Moshtagh et al., 2018; Ukkusuri et al., 2017; Tomsen et al., 2014; Wang et al., 2013; Takizawa et al., 2011; Daganzo & So, 2011; Stepanov & MacGregor Smith, 2009).

Table 2.4 Classification of transportation network post-disaster management studies

		Traffic routing	Traffic routing & scheduling	Demand estimation	Combination & other
Optimization		Li et al. (2019b), He et al. (2018), Moshtagh et al. (2018), Pyakurel et al. (2018), Shahabi & Wilson (2018), Pyakurel & Dhamala (2017), Pyakurel et al. (2017), Wang et al. (2017), Wang et al. (2016), Nassir et al. (2014), Shahabi & Wilson (2014), An et al. (2013), Hadas & Laor (2013), Hua et al. (2013), Luo et al. (2013), Lv et al. (2013), Min & Lee (2013) (*), Wang et al. (2013), Campos et al. (2012), Bretschneider & Kimms (2011), Daganzo & So (2011) (*), Mu et al. (2011), Takizawa et al. (2011), Xie & Turnquist (2011), Ng & Waller (2010), Yazici & Ozbay (2010), Kalafatas & Peeta (2009), Lin et al. (2009), Saadatseresht et al. (2009), Yao et al. (2009), Yin (2009), Chiu et al. (2007), Shen et al. (2007), Sumalee & Kurauchi (2006), Tuydes & Ziliaskopoulos (2006), Feng & Wen (2005), Kim & Shekhar (2005), Mamada et al. (2004), Feng & Wen (2003), Iida et al. (2000), Yamada (1996)	Karabuk & Manzour (2019), Li et al. (2018), Li & Ozbay (2015), Pillac et al. (2015), Bish et al. (2014), Bish & Sherali (2013), Bretschneider & Kimms (2012), Lim et al. (2012)		Lu et al. (2020), Dulebenets et al. (2019), Üster et al. (2018), Bayram et al. (2015), Marcianò et al. (2015), Brachman & Dragicevic (2014), Goerigk et al. (2014), Chen & Xiao (2008) (*)
Simulation	Meso - Macro	Fang & Edara (2013) (*), Balakrishna et al. (2008) (*), Hobeika & Kim (1998) (*)			
	Micro	Henry et al. (2017), Zhang et al. (2014), Lämmel et al. (2010), Sisiopiku (2007), Jha et al. (2004), Pal et al. (2003) (*), Pidd et al. (1996), Sinuany-Stern & Stern (1993)			Kostovasili & Antoniou (2017), Ukkusuri et al. (2017) (*), Yuan et al. (2017), Montz & Zhang (2013), Tu et al. (2013), Li et al. (2011), Hamza-Lup et al. (2008) (*), Wei et al. (2008) (*), M. Chen et al. (2007)
Combination & other		Fahad et al. (2019) (*), Fujisawa et al. (2019), Kim et al. (2017), Sadri et al. (2015), Nassir et al. (2013), Duanmu et al. (2012), Zhou & Liu (2011), Xie et al. (2010), Stepanov & MacGregor Smith (2009), Chiu & Mirchandani (2008) (*), Li et al. (2006), Liu et al. (2006), Cova & Johnson (2003)	Gan et al. (2016), Pillac et al. (2016), Fu et al. (2013), Kimms & Maassen (2011), Afshar & Haghani (2008), Sbayti & Mahmassani (2006), Chiu (2004)	Gudishala & Wilmot (2013), Li et al. (2013), Wilmot & Mei (2004)	Kim et al. (2018), Li et al. (2015), Hsu & Peeta (2014a) (*), Hsu & Peeta (2014b) (*), Tomsen et al. (2014), Hu et al. (2013), Hsu & Peeta (2013) (*), Lambert et al. (2013), Nakanishi et al. (2013), Sadri et al. (2013), X. Chen et al. (2012), Liu et al. (2007) (*), Lahmar et al. (2006), Barrett et al. (2000) (*), Church & Cova (2000), Alam & Goulias (1999) (*), Tufekci (1995) (*)

(*) consideration of a real-time context

Table 2.5 Strategies and parameters involved in post-disaster management studies

	Management strategies							Other parameters					Constr.	
	Lane reversal	Un-interrupted flow	Merging conflicts limitation	Shoulder lanes use	Evacuation priority	Signal timings formulation	Demand regulation	Gradual network loading	Behavioral patterns	Route-choice mechanism	Link failure / incidents	Background traffic	Shelter capacity	Distance from shelter
Dulebenets et al. (2019)					*			*					*	
Fahad et al. (2019)											*			
Fujisawa et al. (2019)											*		*	
Karabuk & Manzour (2019)					*			*						
He et al. (2018)	*												*	
Li et al. (2018)								*						
Moshtagh et al. (2018)	*													*
Pyakurel et al. (2018)	*													
Shahabi & Wilson (2018)											*			
Üster et al. (2018)	*			*									*	
Henry et al. (2017)	*					*		*	*			*		
Kim et al. (2017)	*													
Kostovasili & Antoniou (2017)	*													
Pyakurel & Dhamala (2017)	*													
Pyakurel et al. (2017)	*	*												
Ukkusuri et al. (2017)								*	*	*		*		
Wang et al. (2017)	*										*			
Yuan et al. (2017)								*	*	*			*	*
Gan et al. (2016)								*						
Pillac et al. (2016)	*							*	*		*			
Bayram et al. (2015)													*	*
Li & Ozbay (2015)								*			*			
Li et al. (2015)					*			*						
Marcianò et al. (2015)						*			*	*		*		
Pillac et al. (2015)								*	*		*			
Sadri et al. (2015)									*	*				
Bish et al. (2014)								*	*				*	
Brachman & Dragicevic (2014)									*		*			
Goerigk et al. (2014)								*					*	
Hsu & Peeta (2014a)					*			*	*	*	*	*		
Hsu & Peeta (2014b)					*			*	*	*				
Nassir et al. (2014)					*									
Zhang et al. (2014)									*					
An et al. (2013)	*													
Bish & Sherali (2013)					*			*						
Fang & Edara (2013)	*							*		*		*	*	*
Fu et al. (2013)								*	*					
Gudishala & Wilmot (2013)									*					
Hu et al. (2013)								*					*	
Hua et al. (2013)	*	*	*											
Hsu & Peeta (2013)								*	*	*	*	*		
Lambert et al. (2013)									*			*		
Li et al. (2013)									*					
Luo et al. (2013)		*												
Lv et al. (2013)													*	

	Management strategies							Other parameters					Constr.	
	Lane reversal	Un-interrupted flow	Merging conflicts limitation	Shoulder lanes use	Evacuation priority	Signal timings formulation	Demand regulation	Gradual network loading	Behavioral patterns	Route-choice mechanism	Link failure / incidents	Background traffic	Shelter capacity	Distance from shelter
Min & Lee (2013)	*													
Montz & Zhang (2013)								*						
Nassir et al. (2013)					*									
Sadri et al. (2013)									*	*				
Tu et al. (2013)					*			*	*		*			
Wang et al. (2013)	*				*									
Bretschneider & Kimms (2012)	*	*	*					*						
Campos et al. (2012)		*												
X. Chen et al. (2012)										*				*
Duanmu et al. (2012)								*						
Lim et al. (2012)					*			*						
Bretschneider & Kimms (2011)	*	*									*			
Daganzo & So (2011)					*		*							
Kimms & Maassen (2011)					*			*				*		
Li et al. (2011)													*	
Mu et al. (2011)						*								
Takizawa et al. (2011)													*	
Xie & Turnquist (2011)	*	*												
Ng & Waller (2010)											*			
Xie et al. (2010)	*	*												
Yazici & Ozbay (2010)								*			*	*		
Kalafatas & Peeta (2009)	*	*												
Lin et al. (2009)								*	*					
Saadatseresht et al. (2009)													*	*
Stepanov & MacGregor Smith (2009)								*					*	
Yao et al. (2009)					*									
Afshar & Haghani (2008)								*						
Balakrishna et al. (2008)	*							*			*			
Chen & Xiao (2008)						*								
Chiu & Mirchandani (2008)								*	*	*	*			
Hamza-Lup et al. (2008)	*					*								
Wei et al. (2008)					*	*			*			*	*	
M. Chen et al. (2007)	*					*		*		*	*			
Liu et al. (2007)						*		*		*				
Sisiopiku (2007)							*							
Lahmar et al. (2006)					*				*		*			
Li et al. (2006)						*		*					*	
Liu et al. (2006)				*							*		*	
Sbayti & Mahmassani (2006)								*				*	*	
Sumalee & Kurauchi (2006)							*			*	*			
Tuydes & Ziliaskopoulos (2006)	*							*						
Feng & Wen (2005)							*				*			
Kim & Shekhar (2005)	*													
Chiu (2004)								*						
Jha et al. (2004)											*	*		
Wilmot & Mei (2004)									*					
Cova & Johnson (2003)		*	*			*								

	Management strategies							Other parameters					Constr.	
	Lane reversal	Un-interrupted flow	Merging conflicts limitation	Shoulder lanes use	Evacuation priority	Signal timings formulation	Demand regulation	Gradual network loading	Behavioral patterns	Route-choice mechanism	Link failure / incidents	Background traffic	Shelter capacity	Distance from shelter
Feng & Wen (2003)							*				*			
Pal et al. (2003)	*					*				*				
Barrett et al. (2000)	*			*			*		*		*			
Iida et al. (2000)							*				*			
Alam & Goulias (1999)								*	*		*			
Hobeika & Kim (1998)	*			*				*						
Yamada (1996)													*	
Sinuany-Stern & Stern (1993)	*				*			*		*				

2.5 Conclusions and remarks

Although network management extends from the period preceding to the period succeeding a catastrophe and involves a range of activities aiming at the preservation of the structural integrity of the infrastructure and the enhancement of system performance, most of the literature has until now focused on the study of evacuation operations. Nevertheless, the need for generalized network management in the aftermath of a disruptive event is equally essential and practically more frequent; this premises the consideration of bi-directional traffic movements to accommodate the diverse needs arising, the employment of appropriate management strategies and the combination of different types of performance measures to fit the objectives set, as well as the consideration of users' route choice behavior to more realistically capture the traffic patterns observed in practice. In this context, the literature is still deprived from studies attempting a holistic approach to network management. As such, a framework that explicitly considers the operational state of the network and users' behavioral patterns and attempts a system re-organization on the basis of defined objectives is deemed to advance the current state-of-the-art in disaster management.

3. Route choice models and path generation methods

3.1 Overview

As Prashker & Bekhor (2004) note, traffic assignment has traditionally been based on simple route choice models with the deterministic user equilibrium (DUE) being the most popular among them. According to the latter, route selection is based on perfect knowledge over all arc costs and rational traveler behavior. However, and despite being widely applied, the DUE principle is argued to be inadequate for modeling travel behavior in the case of emergencies (Prashker & Bekhor, 2004), as the disaster characteristics may have a decisive influence on the emergent behavioral responses (Hsu & Peeta, 2013). As Xie & Liu (2014) note, network traffic flows are dynamic in nature and may vary on the basis of demand and supply fluctuations over time. Chen et al. (2011) recognize the same parameters of uncertainty while, quoting Yang & Bell (1998), argue that current research efforts in the network design problem (NDP) have failed accounting for stochasticities.

Supply changes may be caused by weather conditions, traffic incidents, work zones etc., while demand variations may occur due to temporal fluctuations (e.g. time of the day), the organization of special events (e.g. concerts), the provision of traveler information and so on (Chen et al., 2011). The aforementioned sources of uncertainty should be complemented with the inclusion of disaster phenomena. Indeed, Iida et al. (2000) argue that post-disaster traffic patterns deviate from normal, with their observation based on real traffic data from the aftermath of the Kobe earthquake. Li et al. (2006), X. Chen et al. (2012), Chiu & Mirchandani (2012) and Hsu & Peeta (2013), among others, also support that statement. In disaster settings, the physical and / or operational attributes of the network, the diverse needs arising as well as other problem aspects, including, but not limited to, the perceived risk of the disaster threat and its possible consequences (Helsloot & Ruitenberg, 2004), the location of family members and / or close ones (Sorensen & Sorensen, 2007), the existence of an evacuation plan and the available time to react (Helsloot & Ruitenberg, 2004), the provision of complete and precise information to evacuees (Perry & Lindell, 2003), and so on can lead to changes in the travel behavior exhibited. In this respect, it seems reasonable to assume that stochastic equilibrium models may be more appropriate for the representation of real-world problems (Xie & Liu, 2014; Prashker & Bekhor, 2004).

Li et al. (2009) also highlight the importance of properly modeling travel behavior. The authors argue that model assumptions have a clear influence on the estimation and assessment of network performance and, thus, on the network design adopted. However, their focus lies on departure time modeling and not on route choice modeling. Chootinan et al. (2005) investigate the problem from a theoretical perspective using the definition and structure of the NDP. According to them, the NDP is analogous to the Stackelberg game; its leader-follower structure corresponds to the roles of the network planner and users respectively. While the network users wish to minimize their own travel costs, the primary scope of the network planner is the optimization of network performance. During this interaction, "the decisions made by the planner can only influence, not control, the decisions of the network users" (Chootinan et al., 2005). This statement implies that users' behavior is not deterministically determined; instead, travelers' route choice is subject to random errors according to the perceived travel costs. This, in essence, corresponds to the definition of *stochastic user equilibrium (SUE)*: in the SUE, the network users cease switching routes at the time when they cannot further reduce their perceived travel costs, the latter being subject to random errors (Davis, 1994). In the SUE case, not all travelers are assigned to the least cost routes; however, the chances of choosing a lower cost route are better.

Few studies have considered the stochastic NDP. According to the review of Chen et al. (2011) on the subject, most of them focus on the demand variation whereas supply-side uncertainties have been relatively unexplored. Studies that have incorporated a SUE assignment in their formulation include those of Sumalee et al. (2009), Connors et al. (2007), Chen et al. (2006), Clark & Walting (2006) and Chootinan et al. (2005), with Marcianò et al. (2015) and Sumalee & Kurauchi (2006) specifically referring to a disaster management context.

According to Prashker & Bekhor (2004), the very first model of this category is attributed to Daganzo & Sheffi (1977), who attempted to account for travel cost uncertainty. In general, the first SUE models used the *multinomial logit (MNL)* or *multinomial probit (MNP)* formulations for stochastic network assignment. In the late 1990s, route choice modeling was enriched with many discrete choice models (Prashker & Bekhor, 2004); these included modifications of the MNL model, such as the C-logit and the path-size logit (PSL) models, models using the generalized extreme value (GEV) theory, such as the paired combinatorial logit (PCL) and the cross-nested logit (CNL) models, and finally models containing sophisticated formulations of the error terms, such as the logit kernel (LK) or, otherwise referenced, the mixed or hybrid logit model. It must be noted, however, that, due to its inability to capture the correlations among alternatives, the MNL model is considered to be inappropriate for route choice modeling (Prashker & Bekhor, 2004). In real world networks, route overlapping is a common observation, thus leading to a violation of MNL's fundamental assumption of independence of irrelative alternatives (IIA). Nevertheless, the MNL model is still used in stochastic traffic assignment.

3.2 Discrete choice models

Utility theory sets the basis for the formulation of route choice models (Prashker & Bekhor, 2004). By definition, *utility* can be divided into two components: a deterministic one and a random one. Whereas the deterministic component includes all the observable parameters affecting route choice, including the characteristics of the alternatives themselves and of the individuals (Ben-Akiva & Bierlaire, 1999), the error term includes all the "individual perception errors, measurement errors and specification errors" (Prashker & Bekhor, 2004). As a result, utility is a random variable which can be described as follows:

$$U_k^n = V_k^n + \varepsilon_k^n, \forall k \in K^{rs} \quad (3.1)$$

where U_k^n is the utility of individual n for choosing route k, V_k^n and ε_k^n are the deterministic and random components respectively, and K^{rs} is the set of routes k for OD pair (r,s). The deterministic component (omitting superscript n) can be expressed as:

$$V_k = -\theta c_k \quad (3.2)$$

with c_k being the generalized cost function and θ being a positive parameter. In this equation, θ reflects the dispersion among drivers; as θ increases, the variance among the users decreases and route choice tends to become deterministic (best path choice) as in a DUE assignment. On the other hand, as θ decreases, the deterministic component cannot compensate for the error term, leading to a large route choice variance among the drivers. The generalized cost function c_k can be further analyzed as:

$$c_k = \sum_{k \in K^{rs}} c_i \delta_{ik}^{rs} \quad (3.3)$$

where c_i is the cost associated with link i, and $\delta_{ik}^{rs} = 1$ if link i belongs to path k of OD pair (r,s) and zero otherwise.

It must be noted that, if considered advantageous, the aforementioned linear equation describing the deterministic component of utility (eq. (3.2)) can easily be replaced by other, more sophisticated expressions (Prashker & Bekhor, 2004).

3.3 Stochastic route choice models

Stochastic route choice models can generally be categorized into the families of MNP and MNL models. In particular, the intractability of the MNP model in the case of multiple alternatives and the inability of the MNL model to account for similarities among routes, gave rise to the development of advanced MNL-based models dealing with this shortcoming. These models can be summarized in:

- Modifications of the MNL model, such as the C-logit and the PSL model, with route overlapping captured in the deterministic component of the utility function.
- GEV models, such as the CNL, the GNL and the PCL model, with route overlapping captured in the error term of the utility function.

In addition, LK (mixed or hybrid logit) models, with route overlapping captured in the error term of the utility function, were also developed on the basis of the MNP model. In this context, GEV models are more general than the MNL model, with LK models being the most sophisticated of all. The above categorization is illustrated in **Figure 3.3**. Based on the work of Prato (2009), Prashker & Bekhor (2004) and Ben-Akiva & Bierlaire (1999), a brief description of the MNL, C-logit and GEV-based models are provided in the following, while the rest of the route choice models are analyzed in Appendix A.

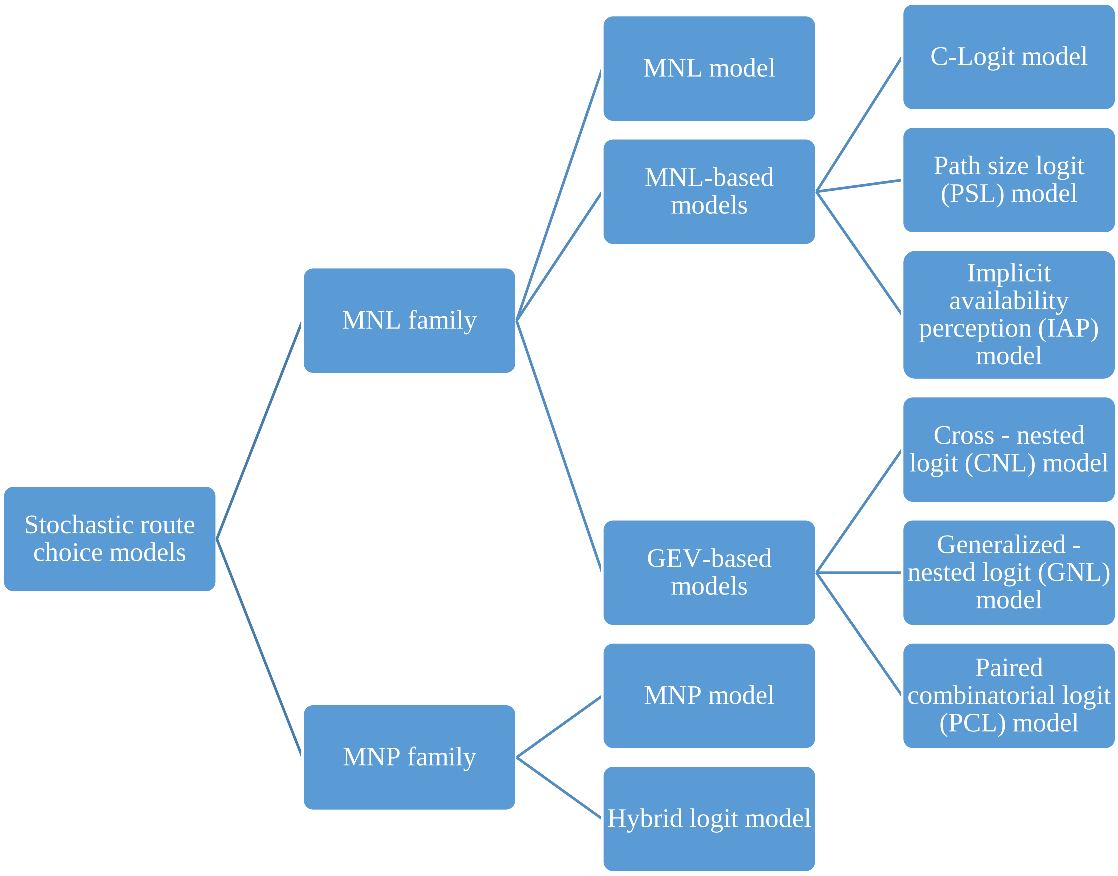


Figure 3.1 Classification of stochastic route choice models

3.3.1 The multinomial logit (MNL) model

The fundamental assumption of the *MNL model* is that the random variables included are independently and identically distributed (IID) Gumbel variables. The Gumbel cumulative distribution function has the form:

$$F(\varepsilon) = e^{-e^{-\mu(\varepsilon-\eta)}} \tag{3.4}$$

where η is the location parameter, and μ is a strictly positive scale parameter. The variance of the distribution is $\pi^2/\left(6\mu^2\right)$. The probability of choosing route k from choice set K^{rs} can be expressed as:

$$P_k = \frac{\exp(\mu V_k)}{\sum_{l \in K^{rs}} \exp(\mu V_l)} \tag{3.5}$$

and the variance-covariance MNL matrix is as follows:

$$\Sigma = \frac{\pi^2}{6\mu^2}\begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix} \tag{3.6}$$

The independence of irrelevant alternatives (IIA) is an inherent characteristic of the MNL model. According to it, "the ratio of the probabilities of any two alternatives is independent of the choice set" (Ben-Akiva & Bierlaire, 1999). That is, for two choice sets $C_1 \subseteq C_n$ and $C_2 \subseteq C_n$, where C_n is the master choice set, and for any alternatives i, j in both C_1 and C_2, it holds that:

$$\frac{P(i|C_1)}{P(j|C_1)} = \frac{P(i|C_2)}{P(j|C_2)} \tag{3.7}$$

The above proposition can be also stated as: "The ratio of the choice probabilities of any two alternatives is unaffected by the systematic utilities of any other alternatives" (Ben-Akiva & Bierlaire, 1999).

When it comes to route choice, the IIA property is considered a deficiency; the MNL model is incapable of accounting for similarities between the routes. This can be a problem, especially in large scale networks, where path overlapping seems to be inevitable. Nevertheless, the MNL model remains popular in stochastic traffic assignment due to its simple form and solution tractability.

3.3.2 Modifications to the multinomial logit (MNL) model

The inability of the MNL model to account for path overlapping can cause distortions in the route choice process. To deal with this problem, the researchers have proposed modifications of the basic model. These are analyzed in the following.

3.3.2.1 The C-Logit model

The *C-Logit model* was developed by Cascetta et al. (1996) as an extension of the MNL model to account for path overlapping. It can be expressed as:

$$P_k = \frac{\exp(V_k - CF_k)}{\sum_{l \in K^{rs}} \exp(V_l - CF_l)} \tag{3.8}$$

where CF_k is a similarity measure (referenced as the commonality factor) between path k and all other paths in set K^{rs} of OD pair (r, s). Cascetta et al. (1996) defined it as:

$$CF_k = \beta \ln \sum_{\substack{k \neq l \\ k,l \in K^{rs}}} \left(\frac{L_{kl}}{\sqrt{L_k L_l}} \right)^{\gamma} \tag{3.9}$$

with L_k and L_l being the length (cost) of paths k and l respectively, L_{kl} being the common length (cost) of the two paths, and β and γ being positive parameters that need to be calibrated. Cascetta et al. (1996) also provided alternative forms for the commonality factor such as:

$$CF_k = \beta \ln \sum\nolimits_{i \in \Gamma_k} (w_i \sum\nolimits_{k \in K^{rs}} \delta_{ik}) \qquad (3.10)$$

$$CF_k = \beta \sum\nolimits_{i \in \Gamma_k} (w_i \ln \sum\nolimits_{k \in K^{rs}} \delta_{ik}) \qquad (3.11)$$

where Γ_k is the sum of all links i comprising path k and w_i is the proportional weight of link i for path k. According to Cascetta et al. (1996), coefficients w_i can be specified in different ways on the basis of the hypotheses made regarding the relative importance of link i for path k. In this context, w_i can be expressed as a fraction of the link length to the total path length. In any case, it must hold that $\sum\nolimits_{i \in \Gamma_k} w_i = 1$. In addition, δ_{ik} equals one if link i lies on path k and zero otherwise. Cascetta (2001) also suggested the following form:

$$CF_k = \beta \ln \left[1 + \sum\nolimits_{k,l \in K^{rs}}^{k \neq l} \left(\frac{L_{kl}}{\sqrt{L_k L_l}} \right) \left(\frac{L_k - L_{kl}}{L_l - L_{kl}} \right) \right] \qquad (3.12)$$

3.3.3 The generalized extreme value (GEV) type models

In an effort to overcome the deficiencies of the MNL model, other logit-based models were developed. These are formulated on the basis of the GEV theorem proposed by McFadden (1978). In the general case, the probability of choosing alternative i can be expressed as:

$$P\left(i \middle| C_n\right) = \frac{e^{V_i} \frac{\partial G}{\partial e^{V_i}} \left(e^{V_1}, ..., e^{V_J}\right)}{\mu G\left(e^{V_1}, ..., e^{V_J}\right)} \qquad (3.13)$$

where J is the number of alternatives in the choice set C_n, and G is a non-negative differentiable function defined on R_+^J. Definition of an appropriate generator function, which satisfies the properties of the GEV theorem, is a prerequisite for the formulation of more general logit functions. These properties are summarized by Ben-Akiva & Bierlaire (1999) as follows:

- G is non-negative.
- G is homogeneous of degree $\mu > 0$.
- $\lim_{x_i \to \infty} G\left(x_1, ..., x_i, ..., x_J\right) = \infty, \forall i = 1, ..., J$.
- The k^{th} partial derivative with respect to k distinct x_i is non-negative if k is odd, and non-positive if k is even, that is, for any distinct $i_1, ..., i_k \in \{1, ..., J\}$ it holds that:

$$(-1)^k \frac{\partial^k G}{\partial x_{i_1} .... \partial x_{i_k}} (x) \leq 0, \forall x \in R_+^J \qquad (3.14)$$

The cross-nested logit (CNL), the generalized-nested logit (GNL) and the paired combinatorial logit (PCL) model belong to this category. These are analyzed in the following.

3.3.3.1 The cross-nested logit (CNL) and the generalized-nested logit (GNL) model

The *CNL model*, proposed by Vovsha (1997), is a generalization of the two-level nested logit model by allowing to an alternative to belong to more than one nest. Later, Wen & Koppelman (2001) presented the *GNL model*, which is more sophisticated than the previous CNL. Both the CNL and the GNL models share the same formulations. In this context, the GNL generator function can be defined as:

$$G(y_1, y_2, ..., y_n) = \sum_{m \in A} \left(\sum_{k \in K^{rs}} (\alpha_{mk} y_k)^{\frac{1}{\mu_m}} \right)^{\mu_m} \tag{3.15}$$

where m is the number of nests, μ_m is the nesting degree (specific for each nest) with $0 \le \mu_m \le 1$, and α_{mk} are the inclusion coefficients which allocate the alternatives to the nests with $0 \le \alpha_{mk} \le 1$. It must hold that:

$$\sum_{m \in A} \alpha_{mk} = 1 \tag{3.16}$$

The GNL generator function satisfies the GEV theorem. The probability of choosing route k can be expressed as:

$$P(k) = \sum_{m \in A} P(m) P(k/m) \tag{3.17}$$

The conditional probability of choosing route k in the case link (nest) m is chosen can be defined as:

$$P(k/m) = \frac{\left(\alpha_{mk} \exp(V_k)\right)^{\frac{1}{\mu_m}}}{\sum_{l \in K^{rs}} \left(\alpha_{ml} \exp(V_l)\right)^{\frac{1}{\mu_m}}} \tag{3.18}$$

and the marginal probability of choosing link (nest) m is:

$$P(m) = \frac{\left(\sum_{k \in K^{rs}} \left(\alpha_{mk} \exp(V_k)\right)^{\frac{1}{\mu_m}} \right)^{\mu_m}}{\sum_{b \in A} \left(\sum_{k \in K^{rs}} \left(\alpha_{bk} \exp(V_k)\right)^{\frac{1}{\mu_m}} \right)^{\mu_m}} \tag{3.19}$$

The MNL model is a special case of the GNL model for $\mu_m = 1$. In the CNL model, μ_m is assumed to be the same across all links and needs to be estimated (Prashker & Bekhor, 1998). For the GNL model, Bekhor & Prashker (2001) defined the nesting coefficient as:

$$\mu_m = 1 - \frac{1}{N_m} \sum_k \alpha_{mk} \tag{3.20}$$

where N_m is the number of routes passing through nest (link) m. As for the inclusion coefficients, Prashker & Bekhor (1998) proposed the following form:

$$\alpha_{mk} = \frac{l_m}{L_k} \delta_{mk} \tag{3.21}$$

where l_m is the link length, L_k is the path length, and δ_{mk} equals one if link m is included in path k and zero otherwise. Inclusion coefficients reflect the impact of path overlapping; by assigning continuous values $0 \le \alpha_{mk} \le 1$, a route is allowed to belong to more than one nest (link). On the other hand, if only binary values (0 or 1) are considered, each route belongs to only one nest, as in the nested logit model.

3.3.3.2 The paired combinatorial logit (PCL) model

The *PCL model* was first proposed by Chu (1989) and also belongs to the category of GEV models. The PCL generator function can be defined as:

$$G(y_1, y_2, ..., y_n) = \sum_{\substack{k=1 \\ k \in K^{rs}}}^{n} \sum_{\substack{j=k+1 \\ j \in K^{rs}}}^{n-1} \left(1-\sigma_{kj}\right) \left(y_k^{\frac{1}{1-\sigma_{kj}}} + y_j^{\frac{1}{1-\sigma_{kj}}} \right)^{1-\sigma_{kj}} \tag{3.22}$$

The probability of choosing route k can be estimated as:

$$P(k) = \sum_{\substack{k \neq j \\ k, j \in K^{rs}}} P(kj) P(k / kj) \tag{3.23}$$

where $P(k / kj)$ is the conditional probability of choosing alternative (route) k, given that pair (k, j) has been chosen, such that:

$$P(k / kj) = \frac{\exp\left(\frac{V_k}{1-\sigma_{kj}}\right)}{\exp\left(\frac{V_k}{1-\sigma_{kj}}\right) + \exp\left(\frac{V_j}{1-\sigma_{kj}}\right)} \tag{3.24}$$

and the marginal probability of choosing pair (k, j) is given as follows:

$$P(kj) = \frac{\left(1-\sigma_{kj}\right)\left[\exp\left(\frac{V_k}{1-\sigma_{kj}}\right) + \exp\left(\frac{V_j}{1-\sigma_{kj}}\right)\right]^{1-\sigma_{kj}}}{\sum_{\substack{l=1 \\ l \in K^{rs}}}^{n-1} \sum_{\substack{m=l+1 \\ m \in K^{rs}}}^{n} \left(1-\sigma_{lm}\right)\left[\exp\left(\frac{V_l}{1-\sigma_{lm}}\right) + \exp\left(\frac{V_m}{1-\sigma_{lm}}\right)\right]^{1-\sigma_{lm}}} \tag{3.25}$$

In the above expressions, σ_{kj} is the similarity measure between alternatives k and j. The MNL is a special case of the PCL model, with $\sigma_{kj} = 0$ for all (k, j) pairs. In the PCL model, each pair (k, j) may exhibit a different similarity relationship from those of the other pairs, a characteristic that is especially attractive in the route choice process. Prashker & Bekhor (1998) formulated the following similarity measure:

$$\sigma_{kj} = \left[\frac{L_{kj}}{\sqrt{L_k L_j}} \right]^{\gamma} \tag{3.26}$$

where L_{kj} is the common length between routes k and j, and γ is a coefficient to be estimated. The above index is developed on the basis of network topology and is flow-independent in order for the GEV theorem to hold. Another formulation for the similarity measure was proposed by Gliebe et al. (1999) as follows:

$$\sigma_{kj} = \frac{L_{kj}}{L_k + L_j - L_{kj}} \tag{3.27}$$

In the above equations, it holds that $0 \le \sigma_{kj} \le 1$. In the case of maximum overlap, σ_{kj} approaches one, while in the case of disjoint paths, σ_{kj} equals zero.

3.4 Stochastic user equilibrium (SUE) formulations

The concept of stochastic user equilibrium (SUE) is inherently based on the assumption of probabilistic route choice. According to Daganzo & Sheffi (1977), SUE can be defined as the state when no driver can improve his / her perceived travel time by unilaterally changing routes. This can be described as:

$$f_k^{rs} = q^{rs} P_k^{rs}, \forall (r,s) \in N, k \in K^{rs} \tag{3.28}$$

$$P_k^{rs} = P(c_k^{rs} \le c_l^{rs}, \forall k, l \in K^{rs}) \tag{3.29}$$

where f_k^{rs} and c_k^{rs} are the flow and cost respectively of travelling on path k between OD pair (r,s), q^{rs} is the demand from r to s, and K^{rs} is the set of paths connecting the pair.

3.4.1 General optimization form

Sheffi & Powell (1982) proposed a general, unconstrained mathematical programming formulation for the SUE. Let $G(N,A)$ be a network, with N being the set of nodes and A being the set of arcs. If q^{rs} is the demand between OD pair (r,s), and x_i and c_i are the flow and travel cost on link i respectively, the SUE model can be defined as:

$$\min \mathrm{Z} = \sum_{i \in A} x_i c_i - \sum_{(r,s) \in N} q^{rs} S^{rs} - \sum_{i \in A} \int_0^{x_i} c_i(w) dw \tag{3.30}$$

where S^{rs} is the satisfaction function between OD pair (r,s) such that:

$$S^{rs} = E\left[\min_{k \in K^{rs}} \left\{ c_k^{rs} \right\} \right] c(x) \tag{3.31}$$

The probability of choosing path k can be defined as:

$$P_k^{rs} = \frac{\partial S^{rs}}{\partial c_k^{rs}} \tag{3.32}$$

with c_k^{rs}, as already defined, being the cost of travelling on path k between OD pair (r,s).

Prashker & Bekhor (2004) note that the above equation is only valid for translational invariant distributions, which means that the shape of the utilities' density function must be independent of the actual measured utilities. Logit functions satisfy this property. Probit functions, however, exhibit this property only in the case of fixed covariance matrix (flow-independent terms).

A solution to the program was presented by Sheffi (1985). Assuming a path cost probability distribution that satisfies the satisfaction function, Sheffi (1985) derived the equilibrium condition by differentiating the objective function with respect to the link flows. It must be noted, that all models presented in the preceding sections satisfy the satisfaction function. However, in the case of logit-based models, the literature also provides alternative optimization formulations.

3.4.2 Logit-based formulations

Fisk (1980) developed a SUE model with the following form:

$$\min Z = \sum_{i \in A} \int_0^{x_i} c_i(w)dw + \frac{1}{\theta} \sum_{(r,s) \in N} \sum_{k \in K^{rs}} f_k^{rs} \ln f_k^{rs} \tag{3.33}$$

$$\text{s.t.} \quad \sum_{k \in K^{rs}} f_k^{rs} = q^{rs}, \forall (r,s) \in N \tag{3.34}$$

$$x_i = \sum_{(r,s) \in N} \sum_{k \in K^{rs}} f_k^{rs} \delta_{ik}^{rs}, \forall i \in A \tag{3.35}$$

$$f_k^{rs} \geq 0, \forall (r,s) \in N, k \in K^{rs} \tag{3.36}$$

where δ_{ik}^{rs} equals one if link i is on path k between OD pair (r,s) and zero otherwise, and all other parameters have already been defined. Fisk (1980) proved the equivalency of the above formulation to the MNL model.

Later, Zhou et al. (2012) extended Fisk's (1980) formulation by proposing a SUE formulation for the C-Logit model:

$$\min Z = \sum_{i \in A} \int_0^{x_i} c_i(w)dw + \frac{1}{\theta} \sum_{(r,s) \in N} \sum_{k \in K^{rs}} f_k^{rs} \ln f_k^{rs} + \sum_{(r,s) \in N} \sum_{k \in K^{rs}} f_k^{rs} cf_k^{rs} \tag{3.37}$$

$$\text{s.t.} \quad \sum_{k \in K^{rs}} f_k^{rs} = q^{rs}, \forall (r,s) \in N \tag{3.38}$$

$$x_i = \sum_{(r,s) \in N} \sum_{k \in K^{rs}} f_k^{rs} \delta_{ik}^{rs}, \forall i \in A \tag{3.39}$$

$$f_k^{rs} \geq 0, \forall (r,s) \in N, k \in K^{rs} \tag{3.40}$$

where cf_k^{rs} is the commonality factor of route k between OD pair (r,s).

3.4.3 GEV-based formulations

Prashker & Bekhor (2000) developed an entropy-based formulation for the CNL SUE model as follows:

$$\min Z = \sum_{i\in A}\int_0^{x_i} c_i(w)dw + \frac{\mu}{\theta}\sum_{(r,s)\in N}\sum_{m\in A}\sum_{k\in K^{rs}} f_{mk}^{rs}\ln\frac{f_{mk}^{rs}}{(\alpha_{mk}^{rs})^{\frac{1}{\mu}}} + \\ + \frac{1-\mu}{\theta}\sum_{(r,s)\in N}\sum_{m\in A}\left(\sum_{k\in K^{rs}} f_{mk}^{rs}\right)\ln\left(\sum_{k\in K^{rs}} f_{mk}^{rs}\right) \tag{3.41}$$

$$\text{s.t.} \quad \sum_{m\in A}\sum_{k\in K^{rs}} f_{mk}^{rs} = q^{rs}, \forall (r,s)\in N \tag{3.42}$$

$$f_{mk}^{rs} \geq 0, \forall (r,s)\in N, m\in A, k\in K^{rs} \tag{3.43}$$

where f_{mk}^{rs} is the flow on path k of nest m between OD pair (r,s), q^{rs} is the demand between OD pair (r,s), c_i and x_i is the cost and flow on link i respectively, α_{mk}^{rs} is the inclusion coefficient of path k in nest m between OD pair (r,s), θ is the dispersion coefficient, μ is the nesting coefficient, and $f_{mk}^{rs}\ln\frac{f_{mk}^{rs}}{\left(\alpha_{mk}^{rs}\right)^{\frac{1}{\mu}}} = 0$ for either $f_{mk}^{rs} = 0$ or $\alpha_{mk}^{rs} = 0$.

An equivalent formulation can also be derived for the GNL SUE model (Bekhor & Prashker, 2001):

$$\min Z = \sum_{i\in A}\int_0^{x_i} c_i(w)dw + \frac{1}{\theta}\sum_{(r,s)\in N}\sum_{m\in A}\sum_{k\in K^{rs}} \mu_m f_{mk}^{rs}\ln\frac{f_{mk}^{rs}}{(\alpha_{mk}^{rs})^{\frac{1}{\mu_m}}} + \\ + \frac{1}{\theta}\sum_{(r,s)\in N}\sum_{m\in A}(1-\mu_m)\left(\sum_{k\in K^{rs}} f_{mk}^{rs}\right)\ln\left(\sum_{k\in K^{rs}} f_{mk}^{rs}\right) \tag{3.44}$$

$$\text{s.t.} \quad \sum_{m\in A}\sum_{k\in K^{rs}} f_{mk}^{rs} = q^{rs}, \forall (r,s)\in N \tag{3.45}$$

$$f_{mk}^{rs} \geq 0, \forall (r,s)\in N, m\in A, k\in K^{rs} \tag{3.46}$$

where μ_m is the nesting coefficient of nest m and all other parameters are equivalent to the CNL formulation.

In accordance with the previous formulations, the PCL model can be described by the following equations (Prashker & Bekhor, 2000):

$$\min Z = \sum_{i\in A}\int_0^{x_i} c_i(w)dw + \frac{1}{\theta}\sum_{(r,s)\in N}\sum_{k\in K^{rs}}\sum_{\substack{j\neq k\\ j\in K^{rs}}}\left(1-\sigma_{kj}\right) f_{k(kj)}^{rs} \ln\frac{f_{k(kj)}^{rs}}{1-\sigma_{kj}} + $$
$$+\frac{1}{\theta}\sum_{(r,s)\in N}\sum_{\substack{k=1\\ k\in K^{rs}}}^{n-1}\sum_{\substack{j=k+1\\ j\in K^{rs}}}^{n}\sigma_{kj}\left(f_{k(kj)}^{rs}+f_{j(kj)}^{rs}\right)\ln\frac{f_{k(kj)}^{rs}+f_{j(kj)}^{rs}}{1-\sigma_{kj}} \tag{3.47}$$

$$\text{s.t.} \quad \sum_{k\in K^{rs}}\sum_{\substack{j\neq k\\ j\in K^{rs}}} f_{k(kj)}^{rs} = q^{rs}, \forall (r,s)\in N \tag{3.48}$$

$$f_{k(kj)}^{rs} \geq 0, \forall (r,s)\in N, k, j\in K^{rs} \tag{3.49}$$

where $f_{k(kj)}^{rs}$ is the portion of flow on route k from route pair (k, j) between OD pair (r,s), σ_{kj} is the similarity index between routes k and j, $f_{k(kj)}^{rs}\ln\frac{f_{k(kj)}^{rs}}{1-\sigma_{kj}} = 0$ for either $f_{k(kj)}^{rs} = 0$ or $\sigma_{kj} = 0$ and, once again, all other parameters are equivalent to the CNL formulation. The aforementioned GEV-based formulations collapse to Fisk's (1980) MNL formulation when $\mu = 1$, for the CNL and GNL models, and $\sigma_{kj} = 0$, for the PCL model.

The general formulation by Sheffi & Powell (1982) can also be applied to the GEV-type models by appropriately formulating the satisfaction function. Prashker & Bekhor (2004) argue the equivalency between the satisfaction function and "composite utility" of GEV models' generator function.

3.5 Path set generation methods

Transportation networks are generally characterized by a large number of links and nodes, as well as complex connectivity settings resulting from the topological and functional correlations between their components. However, during the definition of the available routes and the respective path set for the traffic assignment process, complex network structures pose a problem; even in small networks, path enumeration proves to be challenging. In this respect, two distinct path set generation methods may be followed: the *exhaustive* and the *selective* one. The *exhaustive* approach enumerates all possible paths before proceeding with traffic assignment. In this case, definition of the path choice set is easy, but the model is computationally intensive due to the large number of existing alternatives (Ben-Akiva & Bierlaire, 1999). Moreover, it is behaviorally unrealistic to assume that travelers have knowledge of all possible paths and are eager to use them (Ben-Akiva & Bierlaire, 1999). The *selective* approach, on the other hand, considers only a selection of paths on the basis of them meeting certain criteria. In this context, Prato (2009) makes an overview of existing possibilities in selective route generation and distinguishes between four categories: deterministic shortest path generation methods, stochastic shortest path generation methods, constrained enumeration methods and probabilistic methods. The respective categorization of the path set generation methods is illustrated in **Figure 3.4**.

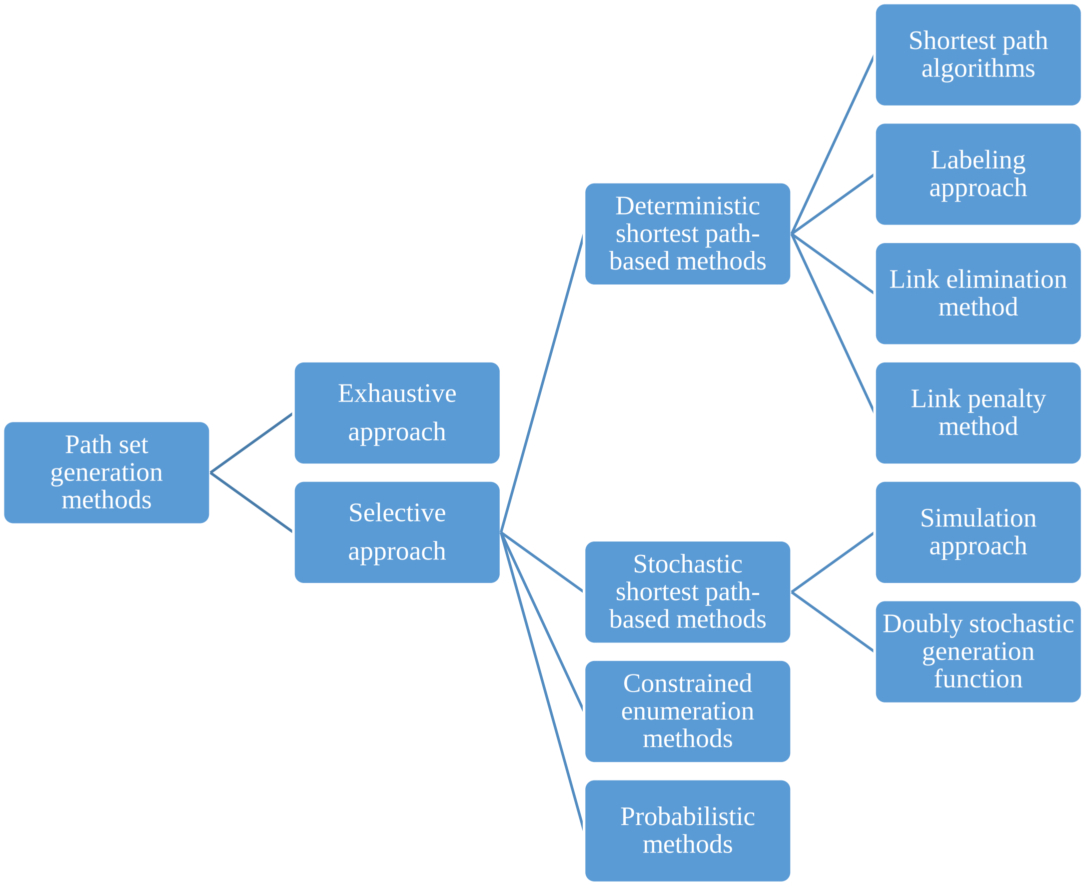


Figure 3.2 Classification of path set generation methods (Prato, 2009)

3.5.1 Deterministic shortest path generation methods

The *deterministic shortest path generation methods* are extensively used in the path generation process and are based on the iterative, criteria-based computation of the shortest paths on a network. In these methods, the solution process is generally heuristic (with the exception of the k-shortest path algorithm), the outcome is deterministic and the OD pairs are processed sequentially (Prato, 2009).

The *k-shortest path method* is perhaps the most popular path generation method. It is based on a link-additive, generalized cost function, usually reflecting the perspective of the traveler (such as travel time or travel distance). The method generates the k-shortest paths connecting each OD pair by successively removing a link from the shortest path and finding the next best one (Prashker & Bekhor, 2004). In this model, travelers are assumed to not consider all possible alternatives, but restrict their choices to those having an affordable variance from the least cost route. In fact, the allowable variance is indicated by the number of *k* generated paths. A serious drawback of the model lies in the possibility of creating "circuitous and extremely similar routes" (Prato, 2009). To circumvent this problem, modifications of the basic formulation have been proposed that account for acyclic paths or increase route heterogeneity. In addition, the model's basic assumption that travelers perceive the utility of the routes in an objective and error-free manner is behaviorally and methodologically unrealistic (Prato, 2009).

The *labeling method* is analogous to the k-shortest path method. According to it, the path choice set consists of individual optimum paths on the basis of distinct objectives. The method was first developed by Ben-Akiva et al. (1984), who used various labels (shortest route, quickest route etc.) while studying the intercity route choice in the Netherlands. Prato (2009) argues that the labeling approach can only partially capture actual route choices due to improper definition of the labels. According to the author, efficient implementation of the algorithm premises a priori knowledge of travel preferences.

The *link elimination method* relies on the repetitive search for the shortest path given that some or all of the links composing the previously defined shortest paths have been eliminated from the network configuration. The approach ensures dissimilarity among the routes to the extent allowed by the link elimination rule (rules are defined on the basis of the researcher’s perception and objectives) (Prato, 2009). The method is attributed to Azevedo et al. (1993), who removed all the shortest-path links before searching for the next best path. Later, Bekhor et al. (2006), Prato & Bekhor (2006) and Frejinger & Bierlaire (2007) developed a modification where only a single link from the shortest path is iteratively removed. Prato (2009) notes that the implementation of the original model poses the problem of network disconnection since the elimination of major crossings may compromise the existence of alternative routes, while the elimination of a single link tends to produce results of high similarity.

Finally, the *link penalty method*, first presented by De la Barra et al. (1993), is also based on the repetitive search for the shortest path. But, instead of employing link elimination, similarity among the routes is prevented through the imposition of a penalty term on the impedances of the links included in the previously identified shortest paths. The model, thus, preserves the possibility of essential links to be part of the shortest routes (due to the non-elimination strategy), while promoting the use of alternative links (Prato, 2009). However, path generation is highly dependent upon the definition of the penalty terms; when a low penalty value is assumed, the algorithm is unable to produce distinct paths, while a high value may cause shorter and more attractive routes to be disregarded in favor of highly unattractive ones.

3.5.2 Stochastic shortest path generation methods

Stochastic shortest path generation methods can be identified by the iterative shortest path computation on a network where travel impedances and individual preferences are assumed to follow a probability distribution (Prato, 2009). In these methods, solution processes are heuristic, the outcome is stochastic and all OD pairs are considered simultaneously (Prato, 2009). Prato (2009) argues that stochastic path generation is a case of importance sampling since the selection probability of a route depends on attributes such as path length or path travel time. As such, a correction term is usually needed to compensate for unequal selection probabilities that may lead to biased results (Bovy et al., 2009; Frejinger et al., 2009; Frejinger, 2007).

The *simulation approach*, proposed by Sheffi & Powell (1982), belongs to this category. As Prato (2009) explains, the method is based on the iterative implementation of Monte-Carlo simulation to draw link travel times from the probit distribution around the overall congested cost function. The algorithm continues by performing an all-or-nothing assignment and by computing the final link flows as the average value from all iterations. The method can potentially generate a large number of attractive alternatives on the basis of an appropriately selected probability distribution and number of draws (Prato, 2009). More specifically, in the case of normal distribution, negative draws must be rejected due to the non-negativity of travel impedances. However, the normal distribution in its truncated form is non-additive in mean and variance. Therefore, other types of distributions such as the log-normal and gamma are preferred in the path generation process (since negative draws are by definition excluded). In this context, Nielsen (2000) argues in favor of the gamma distribution due to the biases induced by truncation. As for the number of draws, there is no unique answer. Ramming (2002) restricts the number of draws to those keeping the computational cost approximately the same as in the link elimination and link penalty methods, while Prato & Bekhor (2006) compute the number of draws on the basis of the method’s ability to generate unique paths.

Nielsen (2000) also introduced the *doubly stochastic generation function method*. The model assumes that, not only are travel costs perceived with error, but also, that this perception differs across the travelers. In this context, the generation function includes two random components: one for the generalized cost function and one reflecting the heterogeneity among users. According to Prato (2009), the method offers diversity in the generated route set, conformity of the routes with observed travel choices and computational efficiency in large networks. On the other hand, calibration of the probability function coefficients can pose a problem, since incorrect values could lead to the generation of unrealistic alternatives. Moreover, the choice of the probability distributions faces the same issues as in the simulation method, with the distribution of the value-of-time arising as an additional consideration; Prato (2009) explains that, when cost and travel time are simultaneously considered, the assumption of a normal cost distribution implies an unacceptable distribution for the value-of-time, where the mean and variance cannot be defined.

3.5.3 Constrained enumeration methods

Constrained enumeration methods assume travelers' route choice behavior to be based on various criteria other than travel cost minimization. In this context, Prato & Bekhor (2006) proposed a branch and bound model, where the branches are formulated with respect to behavioral assumptions. Constraints set by the branches aim at increasing the heterogeneity of the generated paths. A path that satisfies the thresholds posed constitutes a feasible solution to the problem and enters the path choice set. According to Prato (2009), the method generates an exhaustive choice set, which is important for the estimation of utility parameters. However, there exists uncertainty regarding the generation of all attractive routes and the thresholds posed. In addition, the computational burden increases exponentially with the depth of the tree (number of links in the paths), thus, making the algorithm inappropriate for large networks.

3.5.4 Probabilistic methods

Probabilistic path generation methods assign choice probabilities to every route. Prato (2009) notes that the full method, proposed by Manski (1977), is inapplicable to route choice due to the computational burden associated with probability estimations in dense urban networks. The implicit availability / perception (IAP) model, proposed by Cascetta & Papola (2001) and presented in Appendix A, belongs to this category. The model aims at expressing the unavailability or the unawareness of a route in the route choice process. However, Prato (2009) argues that probability estimations actually depend on "socio-economic variables and utility attributes" instead of availability / awareness variables, while Ramming (2002) states that any attempt to associate network parameters to the model does not produce satisfactory results. Furthermore, Frejinger (2007) and Frejinger et al. (2009) estimate link probabilities on the basis of the distance (or generalized cost measure) separating each link from the shortest path connecting an OD pair. Starting from the origin, a route is formulated by the addition of new links on the basis of their choice probabilities. The final route choice probability is calculated as the product of the link probabilities and it is used to compensate for the unequal sampling probabilities (Prato, 2009). Frejinger (2007) and Frejinger et al. (2009) conclude that, employing sampling correction significantly improves the quality of the model. However, Prato (2009) remarks that this should merely be attributed to the configuration of the network used rather than to the effectiveness of the method.

3.6 Conclusions and remarks

With the DUE principle considered inadequate for modeling travel behavior in the case of emergencies (Prashker & Bekhor, 2004), SUE models appear to be more appropriate for the representation of real-world problems (Xie & Liu, 2014; Prashker & Bekhor, 2004). However, and despite the importance of properly modeling travel behavior (Li et al., 2009), research in the NDP has until now failed accounting for stochasticities (Chen et al., 2011). In this respect, the incorporation of a higher degree of realism in transportation management by accounting for some of the stochasticities that are either way present, but possibly exacerbated in a post-disaster setting, is deemed to advance the current research efforts which have generally disregarded randomness from their NDP formulations.

4. Managing a transportation network: conceptual approach and model formulation

4.1 The network design problem (NDP)

In the context of network operations' planning, performance enhancement is pursued through the implementation of appropriate management strategies; these attempt to re-configure the network and / or re-allocate the demand in order to achieve certain performance objectives. The problem formulated in this respect is formally known as the *network design problem (NDP)* and has been recognized as one of the most difficult problems in transportation (Wang et al., 2013; Chootinan et al., 2005; Yang & Bell, 1998). By definition, the NDP involves deciding upon the management strategies implemented on a network for optimizing its performance, while accounting for budget constraints and users' route choice behavior (Wang et al., 2013; Chootinan et al., 2005). User behavior is captured by either deterministic user equilibrium (DUE) or stochastic user equilibrium (SUE) principles (Yang & Bell, 1998). However, as already explained, the DUE principle, despite being widely applied, is argued to be inadequate for modeling travel behavior (Prashker & Bekhor, 2004), especially during emergencies (Hsu & Peeta, 2013). Network flows may fluctuate on the basis of demand and supply changes over time (Xie & Liu, 2014), making it, thus, reasonable to assume that stochastic equilibrium models may be more appropriate for real-world problems (Xie & Liu, 2014; Prashker & Bekhor, 2004).

Depending on the nature of the design variables involved, the NDP can be further distinguished into three sub-types (Farahani et al., 2013; Chootinan et al., 2005):

- the *discrete NDP (DNDP)*, in which the discrete design variables refer to the addition of new links on the network or of new lanes on already existing links, lane reversal and turning restrictions at intersections,
- the *continuous NDP (CNDP)*, with continuous design variables representing road network capacity enhancement, signal timing plans formulation and ramp metering, and
- the *mixed NDP (MNDP)*, which includes both discrete and continuous design variables.

The NDP is typically formulated as a bi-level program. The upper-level corresponds to the network management strategies' implementation scheme (which aims at the maximization of network performance), while the lower-level assigns traffic on the network. The general outline of the NDP may be expressed as follows (Chootinan et al., 2005):

Upper-level problem:

$$Minimize_u F\left(x,u\right) \tag{4.1}$$

subject to:

$$G\left(x,u\right) \leq 0 \tag{4.2}$$

where $x = x\left(u\right)$ is implicitly defined by the lower-level problem:

$$Minimize_u f\left(x,u\right) \tag{4.3}$$

subject to:

$$g\left(x,u\right) \leq 0 \tag{4.4}$$

In the above equations, F, u and G are the objective function, the decision vector and the constraint set for the upper-level sub-program respectively while f, x and g are the objective function, the decision vector and the constraint set for the lower-level sub-program. In the case of stochasticities, the design vectors are treated as random variables instead of assuming deterministic qualities.

4.2 Post-disaster management framework

Despite their possible structural and / or functional degradation, transportation networks are expected to be sufficiently operational in a post-disaster environment, to accommodate the generated needs and provide services that are critical for population safety, community restoration and continuation of activities (Konstantinidou et al., 2019). In this context, generation and application of appropriately formulated management plans arises as significantly important. Their efficacy, however, is largely dependent upon their ability to account for various problem aspects and integrate both the evaluation of performance and the planning of operations; the proposed framework constitutes such an approach.

In particular, the post-disaster management model is formulated as a variant of the Mixed Network Design Problem (MNDP); two distinct management strategies (lane reversal and demand regulation), a multi-aspect measure of performance (including indices of total network travel time (TNTT), satisfied demand (SD) and OD-pair accessibility (OD-A)), stochastic user equilibrium (SUE) traffic assignment (according to the paired combinatorial logit (PCL) model) and iterative path generation (following the link penalty approach) are combined under a vulnerability analysis context in order to provide a re-configured network with re-allocated demand, so that network performance is maximized. The nature of the design variables (lane reversal is a discrete variable whereas demand regulation is continuous) justify the proposed model's classification as an MNDP. Bi-level mathematical programming is used in this respect: the upper-level determines the optimal network management strategies' implementation scheme while the lower-level assigns traffic on the network. The model follows an iterative solution process; the management strategies' implementation scheme derived at each iteration is assessed in terms of the three performance indices. Optimality is reached when no other implementation scheme can achieve improved network performance according to the criteria set.

4.3 Analysis of problem aspects

Discussion of individual problem aspects offers justification and validation over the hypotheses considered and the respective decisions made. These aspects may be broadly categorized into the post-disaster environment identified and the analysis concept and parameters assumed.

4.3.1 Post-disaster environment

The post-disaster network realization sets the basis for the evaluation of network performance. Two parameters are investigated in this respect: the type of network considered and the disruption scenarios assumed.

4.3.1.1 Network type

Due to reasons of computational complexity, the proposed framework is applied on a test network with fifteen nodes and forty eight links. This helps reduce the time associated with the analyses, while still have the necessary background to exhibit the framework's ability to enhance network performance.

4.3.1.2 Network configuration

In a post-disaster setting, the initial network configuration may change due to damages to network components ranging from degradation to full collapse. As a result, post-disaster network states are characterized by three main attributes; the state of individual network components and the number and spatial distribution of component failures.

Failure is generally interpreted in terms of its impact on the component’s ability to fully correspond to its former function. Although most studies assume a binary component state (the component is either operational or not), Du & Nicholson (1997) and Sullivan et al. (2010) are averse to complete link removal, supporting the use of multiple link capacity degradation scenarios. In the latter case, the component is assumed to be partially functional, a state indicated by some sort of capacity reduction or distance increase. In this context, the proposed framework considers both complete and partial component failures. Complete failures are indicated by the removal of the respective link or node from the network, changing, thus, the network’s connectivity settings, while partial failures are depicted as capacity decreases, restricting the amount of traffic that a link can accommodate in a post-disaster state.

In addition, network performance also depends on the way instantaneous component failures are combined with one another to form the surviving network structure. In the proposed framework, post-disaster network configuration is based on the formulation of different disruption scenarios, with the number and spatial distribution of component failures defined arbitrarily. Although these scenarios cannot capture all possible combinations of the three aforementioned parameters, the assumption of scenario-specific cases does not limit the validity of the framework since the focus either way lies in the enhancement of network performance and not on the exact representation of network configuration under a particular catastrophe.

4.3.2 Analysis concept and parameters

Network performance enhancement is eventually achieved on the basis of the problem's NDP formulation. The associated aspects include the type of analysis followed, the management strategies and performance measures considered and the traffic assignment model and path generation method assumed.

4.3.2.1 Type of analysis

The type of analysis used for the estimation of network performance is dependent upon the realization of post-disaster network states. As already explained, there exist five major analysis types: vulnerability, reliability, risk, robustness and resilience. While reliability and risk make use of failure probability estimations and vulnerability and robustness are based on the impact of disruptions, resilience is many times expressed as the fraction of a performance measure in the period preceding or succeeding a catastrophe.

In the present framework, the use of disaster scenarios for the extraction of post-disaster network configurations excludes the possibility of failure probability estimations. As such, performance evaluation is based on the impact of disruptions, making vulnerability the appropriate analysis concept. Vulnerability analysis allows flexibility in problem formulation; the framework exploits this possibility by considering two distinct management strategies, a multi-aspect measure of performance, stochastic user equilibrium assignment and iterative path generation.

4.3.2.2 Management strategies

Performance enhancement strategies may vary on the basis of the generated needs and the operations undertaken, the planner's perspective and any operational or budgetary constraints imposed. The scope, however, always lies in the formulation of an efficient disaster management plan that can account for the characteristics of the disaster setting and correspond to the objectives set. In the present framework, lane reversal and demand regulation are combined to provide an optimally re-configured network with re-allocated demand, so that network performance is maximized.

Lane-based strategies (*contraflow, lane reversal*) have been extensively employed for the re-allocation of roadway capacity along the most heavily congested direction. Their application is pretty straightforward during an evacuation, yet becomes more complicated in the case of bi-directional traffic movements. In this context, lane reversal should account for various parameters, including the demand generated in each direction, lane availability, changes in the network’s connectivity settings, travel distance increase etc. Indeed, the post-disaster environment may force changes in the network's layout and traffic characteristics. The actual demand in the period following a catastrophe cannot be known beforehand and only assumptions can be made about the generated traffic needs. In addition, extensive failures of the infrastructure may lead to inoperability of some routes which, along with the geometrical characteristics of the roadway segments, may affect lane reversal implementation.

Moreover, *demand regulation* refers to the imposition of some kind of control over the allowable traffic movements and may extend from partial to complete access prohibition to an area or part of the network (e.g. highways), or refer to a restriction of travel between the OD pairs. Attention should be paid, though, to the type of vehicles that operate under this policy. Regulation is mainly applied to traffic generated by private vehicles for reasons other than evacuation, while the emergency vehicles retain the potential of unrestricted movement on the network.

4.3.2.3 Network performance indices

Since the efficient planning of network operations is directly related to the extraction of accurate performance estimations, fluctuations of the latter can potentially lead to differentiations in the optimal network management strategies' implementation scheme. It is, thus, important to express performance in a way that can best describe the post-disaster network states, while fitting the objectives set.

Performance can generally be estimated on the basis of flow-dependent or flow-independent measures (Nojima, 1998). Flow-independent measures are easier to estimate since they depend solely on the network's physical state. As such, they avoid the inherently present stochasticities of flow estimations. However, flow-dependent measures are able to capture congestion phenomena and, therefore, provide a more realistic representation of post-disaster network conditions.

In the present framework, performance estimation captures the network's physical and functional degradation with the use of both flow-dependent and flow-independent measures. Three general types of indices are used for that purpose: travel time, satisfied demand and accessibility. These are analyzed in the following.

4.3.2.3.1 Travel time

Travel time measures constitute a fundamental component of transportation network analysis and are commonly used in network performance studies. Especially in the case of disasters, network failures and uncertain travel behavior are expected to result in travel time increases on the network links. It has been observed that, if left un-managed, travel demand can potentially overwhelm the network's capacity and lead to congestion phenomena and gridlocks (Li & Ozbay, 2015; Sadri et al., 2013; Afshar & Haghani, 2008; Zimmerman et al., 2007). In addition, lack of proper traffic management may affect traveler perception on the appropriate routes to choose, increase traffic accidents and lead to confusion.

As opposed to the use of topological (distance-based) indices, travel time measures are better in providing insights regarding network performance in cases of sudden network changes, such as those caused by disasters (Chang, 2003). However, they are susceptible to the inherently present stochasticities of the post-disaster environment; the variability of travel times on the network links can be magnified in a post-disaster state due to congestion phenomena and travelers exhibiting short-term behavior (Chang, 2003; Iida et al., 2000). Realistic assumptions regarding the post-disaster setting and travelers' route choices, though, may set the basis for an integrated network performance evaluation.

In this respect, Omer et al. (2013) assess the resilience of a network subjected to link capacities' decrease as well as demand increase on the basis of environmental, cost and travel time metrics, the latter defined as the percentage difference between OD-pair travel times. Soltani-Sobh et al. (2015) examine network reliability on the basis of different performance measures, including total network travel time, consumer surplus and OD-pair flows, while considering demand and link capacity uncertainties. Donovan & Work (2015) use aggregated taxicab GPS data to notice any possible discrepancies in the hourly, distance-weighted travel times between different parts of a city when compared to analogous data from a typical week. Depending on their extent, these deviations may be indicative of the occurrence of small or more severe events on the roadway network. Burgholzer et al. (2012) analyze the impact of disruptions on intermodal transportation networks. They define multiple performance indices for that purpose; at first, they investigate the impact of a disruption on the entire network while next, they focus on the impact on individual transport units. The latter is addressed through the calculation of the average disruption delay time. As for the former, four indices are developed: total disruption delay time, number of affected transport units, influence distance and influence duration. However, only the first and fourth indices belong to the travel time measures category. Jenelius et al. (2006) approach the problem of network performance evaluation from two perspectives: link importance and municipality exposure. Link importance is calculated on the basis of (a) the post-disaster increase in the generalized travel cost for network's non-cut links and, (b) the fraction of the unsatisfied to the initial, pre-disaster demand for network's cut links. On the other hand, exposure is defined as (a) the average and worst-case travel time increase for a municipality in the case of link disruptions on the network, and (b) the unsatisfied demand originating from a node in the municipality to all other nodes on the network. Jenelius (2009) expands his previous work by generalizing the concepts of importance and exposure to the regional level. Thus, regional importance is defined as the expected total travel time increase for all trips in the network given a disruption in the region. On the other hand, regional exposure can be split into expected total and average exposure, i.e. the total and average travel time increase for trips starting within the region respectively. Jenelius & Mattsson (2012) use a similar concept for estimating network performance in the case of multiple component failures. Kiremidjian et al. (2007a) combine fragility analysis with transport network analysis on a bridge network. At first, the bridge damage states due to a hypothetical seismic event are derived. Then, the sum of vehicle travel times and travel time delays by link type is calculated considering both fixed and variable demand. An analogous methodology for the seismic performance assessment of bridge networks is also followed by Guo et al. (2017), who use the fraction of the post- to the pre-disaster total network travel times as an indicator of traffic cost. Knoop et al. (2012) list different criteria for link-level vulnerability assessment. The authors then attempt a multi-linear fit of the criteria and, considering iterative single-link closures, compare the network performance drop, as this is calculated by the model, with the one actually observed from the simulation. Finally, Snelder et al. (2012) consider single-link failures under different scenarios of roadway capacity reduction and incident duration and calculate the network performance decrease in vehicle loss hours. These can be estimated on the link level or per route, while, when multiplied by the incident occurrence probabilities, the expected vehicle loss hours are derived. In any case, the model takes into account the existence of alternative routes for by-passing the damaged link.

In light of the above, time-based measures arise as a critical aspect of network performance with their ability to reflect both the network's physical degradation and the possible variations of travel patterns. In this context, total network travel time (TNTT), the sum of all vehicles' travel times, is used in the present framework as an index for performance evaluation, with fluctuations of the flow and variations of link travel times resulting in different values of TNTT.

4.3.2.3.2 Satisfied demand

Demand measures can be valuable for the estimation of network performance; while accessibility and travel time indices are descriptive of a network’s general function, the satisfied demand parameter gives more insight into the user needs' satisfaction degree. This is especially important in a post-disaster setting; with evacuation focusing solely on system objectives such as network clearance time minimization, the generalized management framework is broader in scope and aims at ensuring a minimum level of service provision to all kinds of users. As such, quantification of the associated satisfaction degree arises as an important parameter of post-disaster network functionality.

In this context, Vugrin et al. (2014) estimate network resilience as the weighted sum of systemic impact and total recovery effort. In their study, the systemic impact is calculated on the basis of flow-related costs (e.g. travel time delays) as well as by the imposition of a penalty term for each demand unit that cannot be accommodated. Rupi et al. (2014) use an average daily traffic measure and a generalized trip cost measure to evaluate link importance. In the case of disruption, the second measure, referring to a link's global importance, accounts not only for the variation in network's overall cost, but also for the possibility of any unmet demand, assigning, in that case, a value to every missing trip. Kermanshah & Derrible (2016) investigate the impact of seismic events on household-to-work trips by calculating the number of trips being: (a) unaffected, (b) forced to take longer routes, (c) incomplete due to trip origins / destinations becoming isolated, or (d) incomplete due to trip origins / destinations lying in the epicenter of the disaster. Chen & Li (2017) calculate the fraction of (a) the outbound (evacuation) demand to the total exit capacity, and (b) the inbound (first responders) demand to the total entrance capacity, to provide estimates of evacuation difficulty. Chen et al. (2013) use the practical and ultimate capacity concepts to estimate individualized OD-pair demand augmentation rates. While, in the second case, route and destination choice is possible for all network travelers, in the first case, this flexibility is provided only to the additional fraction of the demand, with the initially existing demand pattern being preserved. Jenelius & Mattsson (2012) use a composite measure of unsatisfied demand and travel time. Covering the roadway network with grids of evenly placed cells, they temporarily set unavailable all the links intersecting a particular cell. The unsatisfied demand is then calculated as the one composed by all four components of traffic (internal, inbound, outbound and through traffic for that cell) while travel time delays regard only the through-demand choosing an alternative route (detour) due to cell closure. Jenelius et al. (2006) also use the unsatisfied demand measure. Johansson & Hassel (2010) attempt to model the performance of interdependent infrastructure systems. The model is applied on an electrified railway system with the system's loss of service due to component failure estimated as the fraction of travelers not being able to reach their desired destination. Matisziw & Murray (2009) use a highway network and estimate the maximum flow disrupted due to arc and / or link failure. The model considers multiple, complete component failures but sets an upper bound on the number of facilities to be disrupted. Finally, Miller-Hooks et al. (2012) assume different disruption scenarios on a roadway network, realized by partially inoperable arcs. They proceed with the analysis by accounting for both preparedness and recovery actions under budgetary and travel time constraints. Performance estimation is based on the calculation of the maximum system throughput and the fraction of the satisfied post-disaster demand compared to the pre-disaster case.

In the present framework, the fraction of the satisfied demand in the post-disaster phase provides an additional index for performance assessment, acting as an indicator of the user needs' satisfaction degree. In particular, under the demand regulation strategy, the allowable, between the OD pairs, traffic movements are fractionally adjusted with the aim of SD maximization.

4.3.2.3.3 Accessibility

Despite the inconsistency of terminology across the literature, accessibility generally refers to the ease of approaching a certain destination (Niemeier, 1997) and can be a distance-based measure, a time-based measure or a combination of both. Many researchers argue that accessibility is related to both the transportation system and the land use patterns and as such, any measure developed should account for both of these parameters. Models that focus solely on the transportation system are more related to mobility (Bhat et al., 2000). Scheurer & Curtis (2007) highlight the difference between the two terms; roadways designed for maximum mobility usually provide low accessibility to adjacent land uses; on the other hand, local roads offer increased accessibility but may be apt to congestion.

Accessibility can be used in a variety of concepts (Bhat et al., 2000), with the respective measures formulated according to several criteria (e.g. Geurs & van Wee, 2004; Morris et al., 1979; Weibull, 1976). Different types of classification have been proposed in this regard. Geurs & Ritsema van Eck (2001) have distinguished between infrastructure-based, activity-based and utility-based measures. Bhat et al. (2000) refer to five types of indices: spatial separation, cumulative opportunity, gravity, logsum / utility and time-space ones. Scheurer & Curtis (2007) use a seven-category classification: spatial separation, contour, gravity, competition, time-space, utility and network measures. These categorizations are further analyzed in Appendix B.

In a post-disaster setting, network component failures dictate the need for an integrated approach towards performance assessment, by combining measures that reflect both the network's physical damage state (as in the case of connectivity and distance-based measures) and its impact in terms of flow (as in time-based measures). Accessibility, when used in a disaster management context, has until now focused on various forms of distance-based measures (minimum distance paths in the pre- and post-disaster network states). Distance-based accessibility approaches the problem from a topological point of view, providing thus estimates of post-disaster nodal connectivity, and it is usually weighted by some factor such as population data (e.g. Taylor & Susilawati, 2012) or pre-disaster OD data (e.g. Chang & Nojima, 2001; Chang, 2003). Time-based accessibility measures on the other hand, relate accessibility with travel time on the network's links. However, the stochasticities related with the post-disaster environment and its impact on travel behavior have generally prevented the researchers from the use of this type of models.

Di et al. (2018) develop a flow-based accessibility measure which aims at maximizing the network's total accessible flow (defined as the one that meets the travelers' expectations (travel time budget)) with the construction of additional links. The analysis operates under either the UE or the SO principles and considers both deterministic and stochastic travel demands. Kermanshah & Derrible (2016) use a spatial separation measure to perform accessibility estimations. Starting from the center of a reference location, the authors calculate the percentage difference in accessible areas lying within pre-defined radial distances. Tuzun Aksu & Ozdamar (2014) propose a dynamic model for path-based repair scheduling, which aims at maximizing the cumulative network accessibility during restoration. Only the shortest paths connecting the origin nodes with designated evacuation routes and temporary debris dump sites are considered in the analysis, with priority weights assigned on the basis of restoration urgency. Bono & Gutiérrez (2011) use a distance-based accessibility measure. Covering the network with cells, they first compute the shortest distance from each cell to all other cells. The cumulative cost between two cells is then calculated as the sum of the distance cost between them plus their average cost. The reduced accessibility index due to disruptions is defined as the difference between the cumulative costs of the pre- and post-disaster phases. Chang & Nojima (2001) estimated the post-disaster performance of an earthquake-raided area with three different measures: total length of network open and total and areal based accessibility. The first measure accounts only for the extent of damage. The second measure is based on minimum distance paths and thus takes into account both the extent and the location of the damage. The third measure is designated for areas with nodal accessibility weighted by pre-disaster OD commuter data. The first index can also be modified to include the possibility of detours on the network. Chang (2003) expanded her previous research by formulating a travel time-based accessibility index. The author highlighted the importance of incorporating travel times in post-disaster performance evaluation since they can better evaluate sudden network changes such as those caused by disasters. In this study, accessibility is weighted by the number of job positions located in each traffic analysis zone. A. Chen et al. (2007) developed an accessibility index based on random utility theory. They use a combined travel demand model and derive the expected received utilities for each step of the model (trip generation and destination, mode and route choice) which are used as accessibility indices at the respective levels (network, zonal, OD and OD by mode accessibility). Kondo et al. (2012) used gravity models for formulating the connectivity - potential accessibility index. At first, the impedance between a pair of nodes is calculated on the basis of nodal connectivity (considering link-level reliability) and travel impedance (considering travel distance). The index is then computed by multiplying the opportunities at each node with the impedance between the node pairs and aggregating over the whole network. Sohn (2006) investigates network performance under a flood damage scenario. The accessibility index is a composite measure of travel distance and traffic volume weighted by population data. The advantage of this type of measure, as opposed to purely topological ones, is that accessibility is also evaluated in terms of links' traffic importance. Taylor et al. (2006) use three types of measures to evaluate regional network performance in the case of disruptions. The first one regards changes in the generalized travel cost, as this is expressed through changes in travel times weighted by population data and travel distances. The second one is the Hansen integral accessibility index, using population data as location attractiveness and travel distances as impedances. The last one is the Aria index, a topological index based on the distances from a locality to the nearest service centers of five categories. The studies of Taylor & D' Este (2007) and Taylor & Susilawati (2012) are both based on the previous work of Taylor et al. (2006).

In the present framework, accessibility is assessed in terms of spatial separation measures, as these were extended by Baradaran & Ramjerdi (2001) to include travel cost (see Appendix B). Selection is based upon the characteristics of the post-disaster phase; estimation of opportunities and / or perceived utilities, as these are involved in the other types of accessibility measures, may be difficult in the aftermath of a disaster. This is due to the inherently present stochasticities regarding the disruption impact and how this interferes with the generated needs and users' priorities. In this context, spatial separation measures, expressing travel impedance in terms of both distance and travel time, appear to be proper accessibility indicators for the operations' planning phase, integrating both aspects of network's physical degradation and traffic impact respectively.

4.3.2.4 Traffic assignment and path generation

Traffic assignment follows the principle of stochastic user equilibrium and more specifically the PCL model. The model combines the simplicity and solution tractability of the MNL model while accounting for path overlapping through the use of similarity measures. Formulations proposed by Prashker & Bekhor (1998) and Gliebe et al. (1999) base the latter on flow-independent network characteristics, making their computation easy and disconnecting them from the inherently stochastic traffic flows of the post-disaster phase. In this model, route similarity is estimated through the expression developed by Gliebe et al. (1999). The PCL model characteristics are especially desirable in route choice modeling in dense urban networks where path overlapping seems inevitable and traffic assignment algorithms must keep the computational burden low.

As for the path generation method, this follows the link penalty approach. The reason for the selection of this method is twofold. First, on a functionally degraded network, satisfaction of the user needs may premise the formulation of paths with a limited (according to the penalty value assumed) similarity degree. The link penalty approach acts in favor of this requirement; by penalizing the impedances of the links lying on the already formulated paths, diversity of the generated choice set is promoted. Second, user preferences and needs should be a primary, but not the sole, criterion when devising disaster management plans; decisions of the network planner should also be considered, despite them being often, to some extent, overwritten by the actual user behavior. Given the involvement of the planner in the final network configuration, a deterministic approach for the generation of the path choice set is argued to be more appropriate.

In the following, the integrated MNDP for the management of a post-disaster network is developed. The problem's mathematical formulation along with the sets, parameters and decision variables used are analytically described and discussed. The flowchart of the algorithmic steps along with the flowchart of the path generation process are provided next.

4.4 Model formulation

Let $G(N,A)$ be a directed network, where N is a set of nodes and A is an ordered set of arcs. For each directed arc (i,j), there exists a length d_{ij}, a free flow travel time $t_{f,ij}$, a capacity c_{ij} and an initial number of lanes l_{ij}. Also, let $N_1 \subseteq N$ be a subset of nodes being the network's centroids. For two centroids $(r,s) \in N_1$, the corresponding OD demand is denoted as q^{rs} and the associated OD matrix as $OD = \{q^{rs}\}, \forall (r,s) \in N_1$. With respect to network assignment, flow and travel time per link are defined as x_{ij} and t_{ij} respectively. Also, let $K_{h,pr}$ be a set of high priority paths connecting the special importance nodes of subset N_{sp} with specific nodes of subset N_1 and K be the set comprising all paths on G. In the model, d_k^{rs} and t_k^{rs} are the length of and travel time on path k between OD pair (r,s) while w^{rs} is the destination weight of node s for travelers originating from node r. In addition, $\delta_{ij,k}^{rs} = \{0,1\}$ is defined, with $\delta_{ij,k}^{rs} = 1$ if link (i,j) is part of path k between OD pair (r,s). Y and Z are the objective functions for the upper and lower levels respectively.

The problem's design focus is: (a) the re-distribution of lanes along the links, (b) the adjustment of the demand between network's OD pairs, and (c) the accomplishment of the best possible overall OD-pair accessibility level, with special emphasis placed on the access to the network's special importance nodes (corresponding to facilities which are vital for population safety, community restoration and continuation of activities such as hospitals, police and fire stations, shelters and so on). In this context, y_{ij} is the number of lanes along each directed arc (i,j) after the optimization process, and φ^{rs} is the demand adjustment rate between OD pair (r,s). The sets, parameters and variables used in the model are listed in **Table 4.1**.

Table 4.1 Problem's notation

Symbol	Description
Sets	
N	set of network nodes
N_1	set of network centroids
N_{sp}	set of network special importance nodes
A	set of network arcs
K	set of network paths
$K_{h,pr}$	set of network high priority paths
Parameters	
Y	upper-level objective function
Z	lower-level objective function
d_{ij}	length of link (i, j)
l_{ij}	number of existing lanes on link (i, j)
c_{ij}	capacity of link (i, j)
$t_{f,ij}$	free flow travel time on link (i, j)
t_{ij}	travel time on link (i, j)
x_{ij}	flow on link (i, j)
q^{rs}	origin - destination demand between OD pair (r,s)
d_k^{rs}	length of path k connecting OD pair (r,s)
t_k^{rs}	travel time on path k connecting OD pair (r,s)
$\delta_{ij,k}^{rs}$	indicator of link (i, j), being part of path k between OD pair (r,s) $\left(\delta_{ij,k}^{rs} = 0\, or\, 1\right)$
α	weighting coefficient $(0 \le \alpha \le 1)$
w^{rs}	destination weight of node s for travelers originating from node r
m_2, m_3	BPR function parameters
w_1, w_2, w_3	weighting coefficients
$f_{k(km)}^{rs}$	flow on path k of path set (k,m) between OD pair (r,s)
P_k^{rs}	probability of choosing path k between OD pair (r,s)
P_{km}^{rs}	marginal probability of choosing path set (k,m) between OD pair (r,s)
$P_{k/km}^{rs}$	conditional probability of choosing path k, given that path set (k,m) between OD pair (r,s) is chosen
V_k^{rs}	deterministic component of utility for path k between OD pair (r,s) $\left(V_k^{rs} = -\theta c_k^{rs}\right)$
θ	dispersion coefficient (indicates the variance among drivers)
c_k^{rs}	generalized cost of path k between OD pair (r,s)
σ_{km}^{rs}	similarity index between paths k and m of path set (k,m) connecting OD pair (r,s)
d_{km}^{rs}	length of the common segment between paths k and m of path set (k,m) connecting OD pair (r,s)
Decision variables	
y_{ij}	number of lanes on link (i, j)
φ^{rs}	demand adjustment rate between OD pair (r,s)

The upper level optimization problem is formulated as follows:

$$\min Y = w_1 \sum_{(i,j)\in A} x_{ij} t_{ij} - w_2 \sum_{(r,s)\in N_1} \varphi^{rs} q^{rs} + \\ + w_3 \left[\alpha \sum_{(r,s)\in N_1} \sum_{k\in K} w^{rs} d_k^{rs} + (1-\alpha) \sum_{(r,s)\in N_1} \sum_{k\in K} w^{rs} t_k^{rs} \right] \tag{4.5}$$

subject to:

$$y_{ij} = \begin{cases} l_{ij} + l_{ji} - y_{ji} \geq 0, if\, \delta_{ij,k}^{rs} = 0, y_{ji} \geq 0 \\ l_{ij} + l_{ji} - y_{ji} \geq 1, if\, \delta_{ij,k}^{rs} = 1, y_{ji} \geq 1 \end{cases}, \forall (i,j) \in A, k \in K_{h,pr}, (r,s) \in N_1 \tag{4.6}$$

$$\sum_{j\in N} y_{ij} \geq 1, \forall (i,j) \in A \tag{4.7}$$

$$\sum_{j\in N} y_{ji} \geq 1, \forall (j,i) \in A \tag{4.8}$$

$$y_{ij} \in Z, \forall (i,j) \in A \tag{4.9}$$

$$c_{ij} = c_{ij}(y_{ij}), \forall (i,j) \in A \tag{4.10}$$

$$w^{rs} = \begin{cases} 1, if\; s \in N_{sp}, r \in N_1 \\ \dfrac{\varphi^{rs} q^{rs}}{\sum_{\substack{t\neq r \\ (r,t)\in N_1}} \left(\varphi^{rt} q^{rt}\right)}, otherwise, \forall (r,s) \in N_1 \end{cases} \tag{4.11}$$

$$d_k^{rs} = \sum_{\substack{i\neq j \\ (i,j)\in A}} d_{ij} \delta_{ij,k}^{rs}, \forall k \in K, (r,s) \in N_1 \tag{4.12}$$

$$t_k^{rs} = \sum_{\substack{i\neq j \\ (i,j)\in A}} t_{ij} \delta_{ij,k}^{rs}, \forall k \in K, (r,s) \in N_1 \tag{4.13}$$

$$\delta_{ij,k}^{rs} = \begin{cases} 1, if\; link\,(i,j)\, belongs\, to\; path\, k \\ 0, otherwise \end{cases}, \forall (i,j) \in A, k \in K, (r,s) \in N_1 \tag{4.14}$$

The lower level traffic assignment formulation is expressed as:

$$\min Z = \sum_{(i,j)\in A} \int_0^{x_{ij}} t_{ij}(w)dw + \frac{1}{\theta} \sum_{(r,s)\in N_1} \sum_{k\in K} \sum_{\substack{m\neq k \\ m\in K}} \left(1-\sigma_{km}^{rs}\right) f_k^{rs} \ln\left(\frac{f_k^{rs}}{1-\sigma_{km}^{rs}}\right) + \\ + \frac{1}{\theta} \sum_{(r,s)\in N_1} \sum_{\substack{k=1 \\ k\in K}}^{n-1} \sum_{\substack{m=k+1 \\ m\in K}}^{n} \sigma_{km}^{rs} \left(f_k^{rs} + f_m^{rs}\right) \ln\left(\frac{f_k^{rs} + f_m^{rs}}{1-\sigma_{km}^{rs}}\right) \tag{4.15}$$

subject to:

$$\sum_{k\in K} f_k^{rs} = \varphi^{rs} q^{rs}, \forall (r,s) \in N_1 \tag{4.16}$$

$$f_k^{rs} = \varphi^{rs} q^{rs} P_k^{rs}, \forall k \in K, (r,s) \in N_1 \tag{4.17}$$

$$P_k^{rs} = \sum_{\substack{m \neq k \\ m,k \in K}} P_{km}^{rs} P_{k/km}^{rs}, \forall (r,s) \in N_1 \tag{4.18}$$

$$P_{km}^{rs} = \frac{\left(1-\sigma_{km}^{rs}\right)\left[\exp\left(\frac{V_k^{rs}}{1-\sigma_{km}^{rs}}\right)+\exp\left(\frac{V_m^{rs}}{1-\sigma_{km}^{rs}}\right)\right]^{1-\sigma_{km}^{rs}}}{\sum_{\substack{l=1 \\ l \in K}}^{n-1}\sum_{\substack{p=l+1 \\ p \in K}}^{n}\left(1-\sigma_{lp}^{rs}\right)\left[\exp\left(\frac{V_l^{rs}}{1-\sigma_{lp}^{rs}}\right)+\exp\left(\frac{V_p^{rs}}{1-\sigma_{lp}^{rs}}\right)\right]^{1-\sigma_{lp}^{rs}}}, \forall k,m \in K, (r,s) \in N_1 \tag{4.19}$$

$$P_{k/km}^{rs} = \frac{\exp\left(\frac{V_k^{rs}}{1-\sigma_{km}^{rs}}\right)}{\exp\left(\frac{V_k^{rs}}{1-\sigma_{km}^{rs}}\right)+\exp\left(\frac{V_m^{rs}}{1-\sigma_{km}^{rs}}\right)}, \forall k,m \in K, (r,s) \in N_1 \tag{4.20}$$

$$\sigma_{km}^{rs} = \frac{d_{km}^{rs}}{d_k^{rs} + d_m^{rs} - d_{km}^{rs}}, \forall k,m \in K, (r,s) \in N_1 \tag{4.21}$$

$$f_k^{rs} \geq 0, \forall k \in K, (r,s) \in N_1 \tag{4.22}$$

$$x_{ij} = \sum_{(r,s) \in N_1} \sum_{k \in K} f_k^{rs} \delta_{ij,k}^{rs}, \forall (i,j) \in A \tag{4.23}$$

$$t_{ij} = t_{f,ij}\left(1 + m_2\left(\frac{x_{ij}}{c_{ij}}\right)^{m_3}\right), \forall (i,j) \in A \tag{4.24}$$

Eq. (4.5) corresponds to the upper-level objective function. This is formulated as the weighted sum of three parts: minimization of TNTT, maximization of SD and maximization of OD-A. These three indices act as a multi-aspect measure of performance, catching different parameters of network functionality. More specifically, TNTT serves as a time-based criterion to account for the physical degradation of network infrastructure and the possible variations of travel patterns, as deviations in both parameters would have a clear effect on the travel time experienced. In addition, the proportion of satisfied demand in the post-disaster phase acts as an indicator of the travelers' degree of accommodation. Demand multipliers are applied at the source nodes, which adjust (lower) the initially generated demand to that which better serves the scope of network performance maximization, as this is expressed through the upper-level objective function. In this respect, different regulation rates are defined for each of the network's OD pairs, also on the basis of the system-wide objective of SD maximization. Finally, the accessibility index consists of two terms, a distance-based and a travel time-based one. This twofold approach aims to, once again, capture the impact of a disaster on the network's structural and functional degradation. Both terms are weighted by the coefficient of eq. (4.11) as well as by an additional factor α, determining their relative importance. As for the sign of the accessibility term, since accessibility maximization is achieved through the minimization of the travel distance of and the travel time on the paths connecting each OD pair, the respective term must yield a minimum. Weighting factors w_1, w_2, w_3 are used for the three objective function components, to adjust their influence on the estimation of network performance.

Path construction in the model follows the link penalty approach, with the generated route set distinguished into two categories: high priority and low priority paths. Path classification is made on the basis of node importance. More specifically, high priority paths are defined as those connecting the network's special importance nodes of subset N_{sp} with specific nodes of subset N_1, while low priority paths comprise the rest of the paths formulated. In the model, special importance nodes correspond to facilities which are vital for population safety, community restoration and continuation of activities such as hospitals, police and fire stations, shelters and so on. Due to their criticality, attention must be paid to the paths serving them in terms of their functional characteristics and configuration. These are addressed by ensuring, to the best degree possible, high accessibility to these facilities while lane re-allocation premises the possibility of bi-directional traffic movements. Links forming the paths may be part of both types; high and low priority paths are not necessarily disjoint. In this context, eq. (4.6) defines the number of lanes per directional link. In the case of links belonging to high priority paths, however, eq. (4.6) excludes the possibility of contraflow operations by ensuring the existence of at least one lane per direction. Eq. (4.7) and eq. (4.8) ensure that there is at least one lane emanating from or heading towards each network node respectively, emphasizing, thus, the need to retain network's connectivity. Eq. (4.9) restricts the decision variable to be an integer. Eq. (4.10) sets link capacity. Eq. (4.11) calculates the weights for each destination node on the basis of both its importance and the demand at the originating node. Eq. (4.12) calculates path lengths, while the same applies to eq. (4.13) with respect to path travel times. Eq. (4.14) is an indicator of whether a link belongs to a path.

Eq. (4.15) corresponds to the lower-level objective function of the traffic assignment process and constitutes the entropy-based formulation of the paired combinatorial logit (PCL) model. Eq. (4.16) restricts the sum of the path flows between an OD pair to be equivalent to the demand generated between that pair. Eq. (4.17) defines the flow on a path between an OD pair to be analogous to the demand generated between that pair as well as to the probability of choosing that path. As indicated by eq. (4.18), in the PCL model, the probability of choosing path k from route pair (k,m) between OD pair (r,s) is based on: (a) the marginal probability of choosing pair (k,m) from the set of paths connecting OD pair (r,s) (eq. (4.19)) and, (b) the conditional probability of choosing path k, given that pair (k,m) is chosen (eq. (4.20)). Eq. (4.21) is a similarity measure between the paths composing each route pair. Eq. (4.22) restricts path flows to be positive, while eq. (4.23) calculates the flow on each link. Finally, eq. (4.24) is the Bureau of Public Roads (BPR) function.

4.4.1 Objective function normalization

Since the objective function components have different measurement units and orders of magnitude, these are transformed into their dimensionless, normalized forms according to the expression (Proos et al., 2001):

$$Z_{k,norm} = \frac{Z_k}{\left|Z_{k,\max}\right|} \tag{4.25}$$

where $Z_{k,norm}$ is the normalized value of component Z_k lying in the $[0,1]$ interval, and $\left|Z_{k,\max}\right|$ is the maximum possible value of Z_k without constraint violations. Maximum values for the TNTT and OD-A components are derived from the respective calculations on the non-optimized, post-disaster network, since these will certainly exceed the ones achieved after the optimization process. As for the maximum SD value, this equals the initial, non-adjusted total network demand. This is due to the nature of the demand regulation strategy, according to which, any SD value derived on the optimized network cannot possibly exceed the respective one generated right at the aftermath of the catastrophe.

4.4.2 Problem flowchart

Figure 4.1 illustrates the flowchart of the problem's consecutive steps. More specifically, a disaster scenario is first devised, with the respective network attributes (N, A, d_{ij}, l_{ij}, c_{ij}, $t_{f,ij}$), in addition to other parameters regarding problem hypotheses (w_1, w_2, w_3, α, m_2, m_3, q^{rs}, θ, N_{sp}, N_1), used as model inputs. Then, a number of calculations related to the non-optimized post-disaster network are made; these include the computation of the three performance indices as well as the extraction of the shortest paths between the special importance nodes of subset N_{sp} with specific nodes of subset N_1. Next, the decision variable matrices are created and their respective upper and lower bounds are determined. These steps set the problem environment. The mathematical formulations of the MNDP, including the upper- (eq. (4.5)) and lower-level (eq. (4.15)) objective functions and the rest of the mathematical expressions (eq. (4.6) - (4.14) and (4.16) - (4.24)), are defined, along with the specification of the parameters used in the GA (population size, initial population generation function and range, crossover and mutation functions and rates, termination criteria). Then, the model is ready for the optimization process to start. The initial population of candidate solutions is created (y_{ij} and φ^{rs} decision variables) and the network is re-configured. Following the link penalty approach, the path set between all network nodes is defined and the upper- and lower-level objective functions are calculated. During this process, if the termination criteria are met, the procedure stops and the best solutions found are finalized. Otherwise, the algorithm proceeds with the next generation and another optimization run starts. The final output comprises the decision variables and the objective function values of all Pareto front solutions, with special emphasis placed on the one minimizing the upper-level objective function.

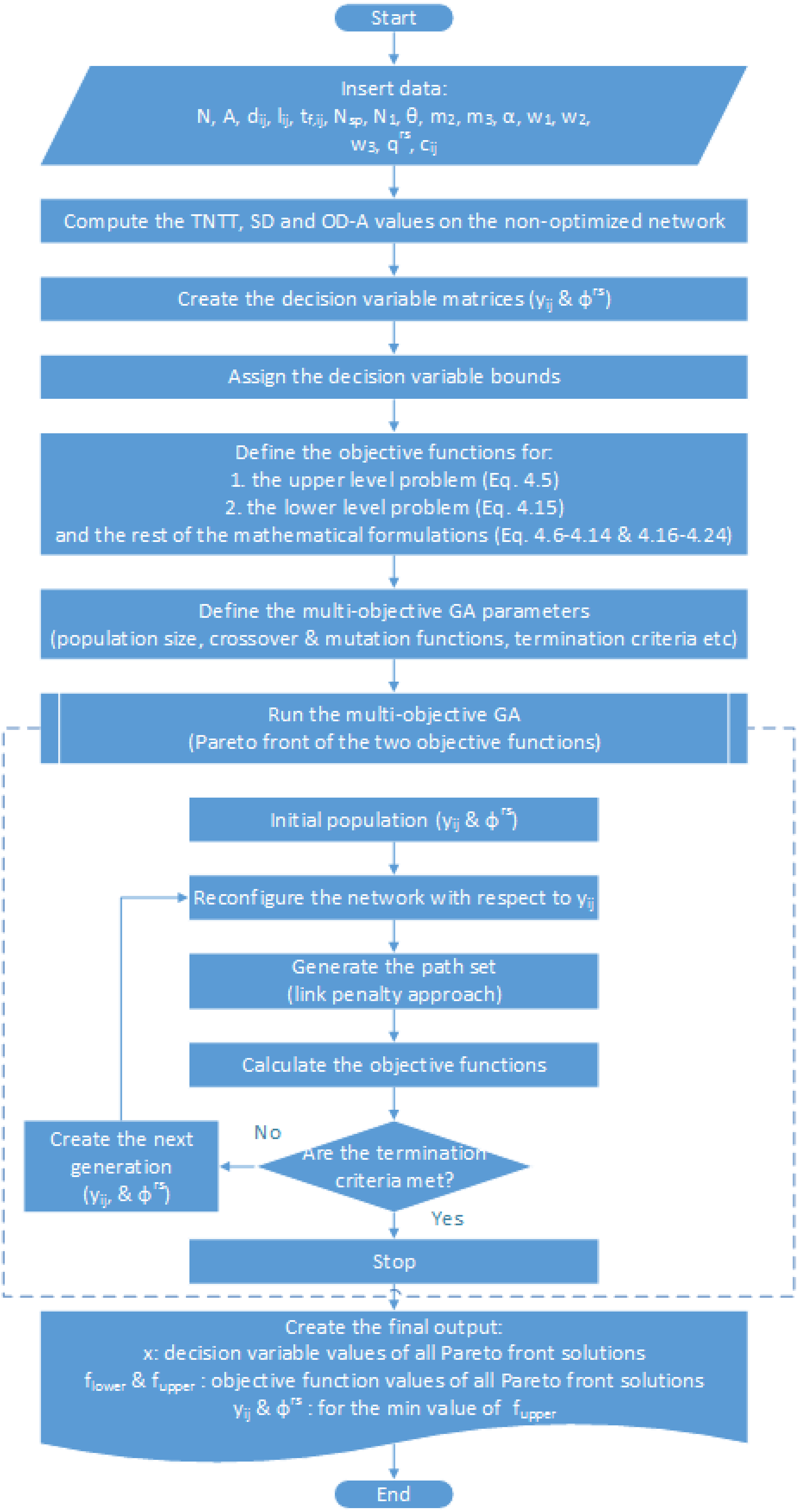
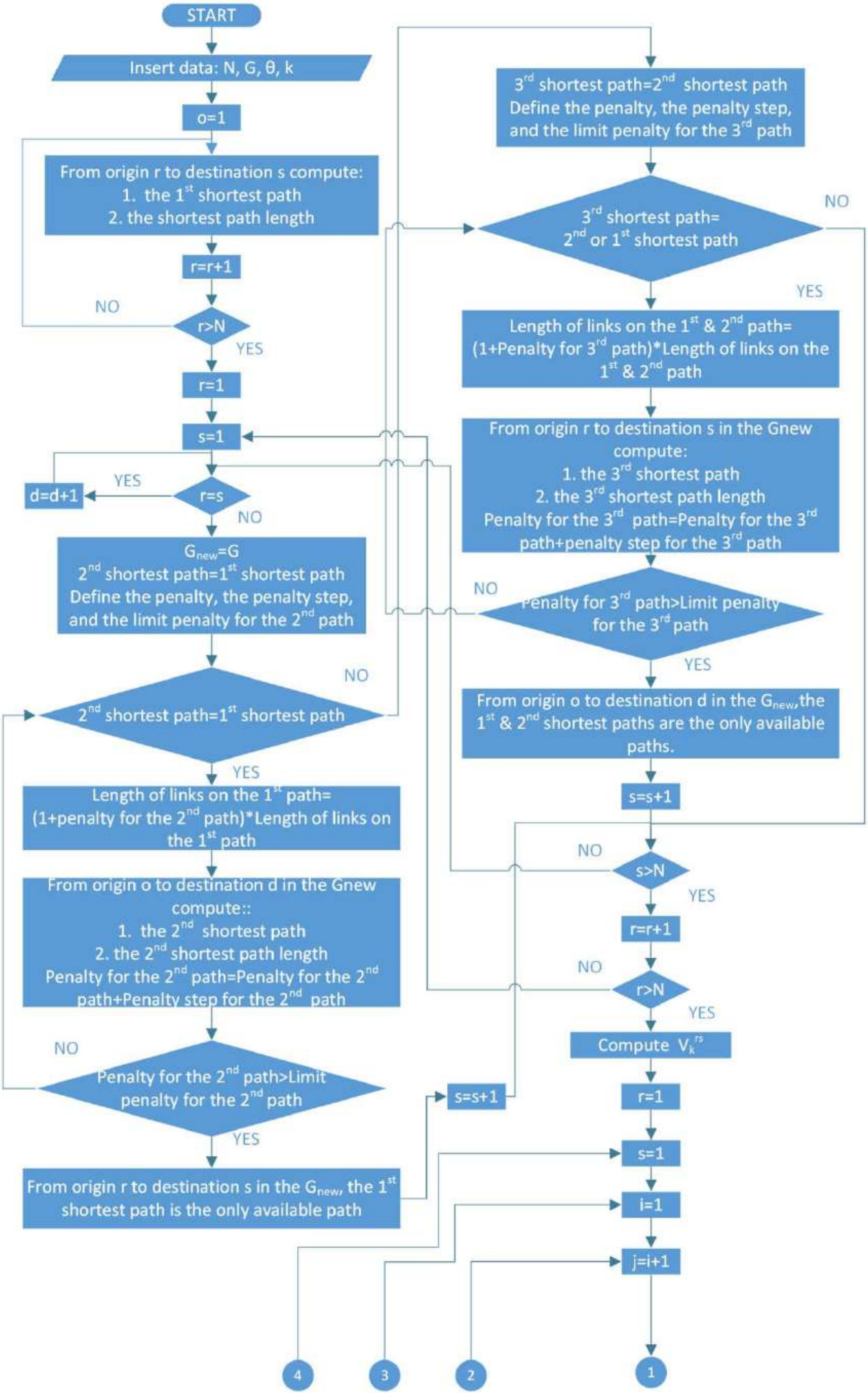


Figure 4.1 Flowchart of the post-disaster management problem

4.4.3 Computational steps for the path generation

Finding a set of k spatially dissimilar paths is a fundamental, yet computationally intensive, part of the proposed model. With every iteration, lane reversal initiates a change in the y_{ij} decision variables and, thus, causes the formation of a "new" network on which the k shortest paths are to be found. The iterative penalty method (IPM), based on the repetitive application of the appropriate shortest path algorithm, is used for that purpose. According to it, after each application of the algorithm, a (cumulative) penalty is imposed on the impedance of the links formulating the, up to that moment, generated paths; formulation of the succeeding paths is based on these augmented impedance values. The flowchart of the algorithm is illustrated in **Figure 4.2**.

According to the figure, at each iteration, the algorithm starts by reading the necessary data; these include the number of nodes N, the graph configuration G, the dispersion coefficient θ and the number of paths to be formulated k. The penalty value, the penalty step and the penalty limit value are defined as well. Then, a conventional shortest path algorithm is employed, with the first (best) paths being calculated for all OD pairs simultaneously. The rest $(k-1)$ paths are determined for each OD pair successively. The penalty factor is applied to the length of the links comprising the first paths, resulting in an updated network. Then, the algorithm is applied on this "new" network and the potential second set of paths is derived. For each individual OD pair, if the second path coincides with the first one, the penalty factor increases by the penalty step assumed and the process is repeated until either a new path is derived or the penalty factor reaches its limit value. The latter case implies that there does not exist any other path, except for the first one, for the examined case. The process is repeated for all network pairs before the algorithm proceeds in search of the third set of paths. Similar to the procedure described above, the difference in this case lies in that, for each OD pair, the potential third path is compared with both the first and the second ones previously defined. If a third path can still not be extracted even after the penalty factor has reached its limit value, it is concluded that, for the examined OD pair, definition of a third path is not possible. Afterwards, having determined all k spatially dissimilar paths, the algorithm computes for each OD pair (r,s), the similarity index σ_{km}^{rs} between paths k and m of path set (k,m), the marginal probability P_{km}^{rs} of choosing path set (k,m), the conditional probability $P_{k/km}^{rs}$ of choosing path k given that path set (k,m) is chosen, and finally, the probability P_k^{rs} of choosing path k. The results ultimately exported by the algorithm refer to all network pairs and include the k spatially dissimilar paths along with their cost, the similarity indices σ_{km}^{rs}, and the probabilities P_k^{rs} of choosing path k.


START
Insert data: N, G, θ, k
o=1
From origin r to destination s compute:
1. the 1st shortest path
2. the shortest path length
r=r+1
r>N
NO
YES
r=1
s=1
r=s
YES
d=d+1
NO
Gnew=G
2nd shortest path=1st shortest path
Define the penalty, the penalty step, and the limit penalty for the 2nd path
2nd shortest path=1st shortest path
NO
YES
Length of links on the 1st path=(1+penalty for the 2nd path)*Length of links on the 1st path
From origin o to destination d in the Gnew compute::
1. the 2nd shortest path
2. the 2nd shortest path length
Penalty for the 2nd path=Penalty for the 2nd path+Penalty step for the 2nd path
Penalty for the 2nd path>Limit penalty for the 2nd path
NO
YES
From origin r to destination s in the Gnew, the 1st shortest path is the only available path
s=s+1
3rd shortest path=2nd shortest path
Define the penalty, the penalty step, and the limit penalty for the 3rd path
3rd shortest path=2nd or 1st shortest path
NO
YES
Length of links on the 1st & 2nd path=(1+Penalty for 3rd path)*Length of links on the 1st & 2nd path
From origin r to destination s in the Gnew compute:
1. the 3rd shortest path
2. the 3rd shortest path length
Penalty for the 3rd path=Penalty for the 3rd path+penalty step for the 3rd path
Penalty for 3rd path>Limit penalty for the 3rd path
NO
YES
From origin o to destination d in the Gnew, the 1st & 2nd shortest paths are the only available paths.
s=s+1
s>N
NO
YES
r=r+1
r>N
NO
YES
Compute Vk rs
r=1
s=1
i=1
j=i+1
4
3
2
1

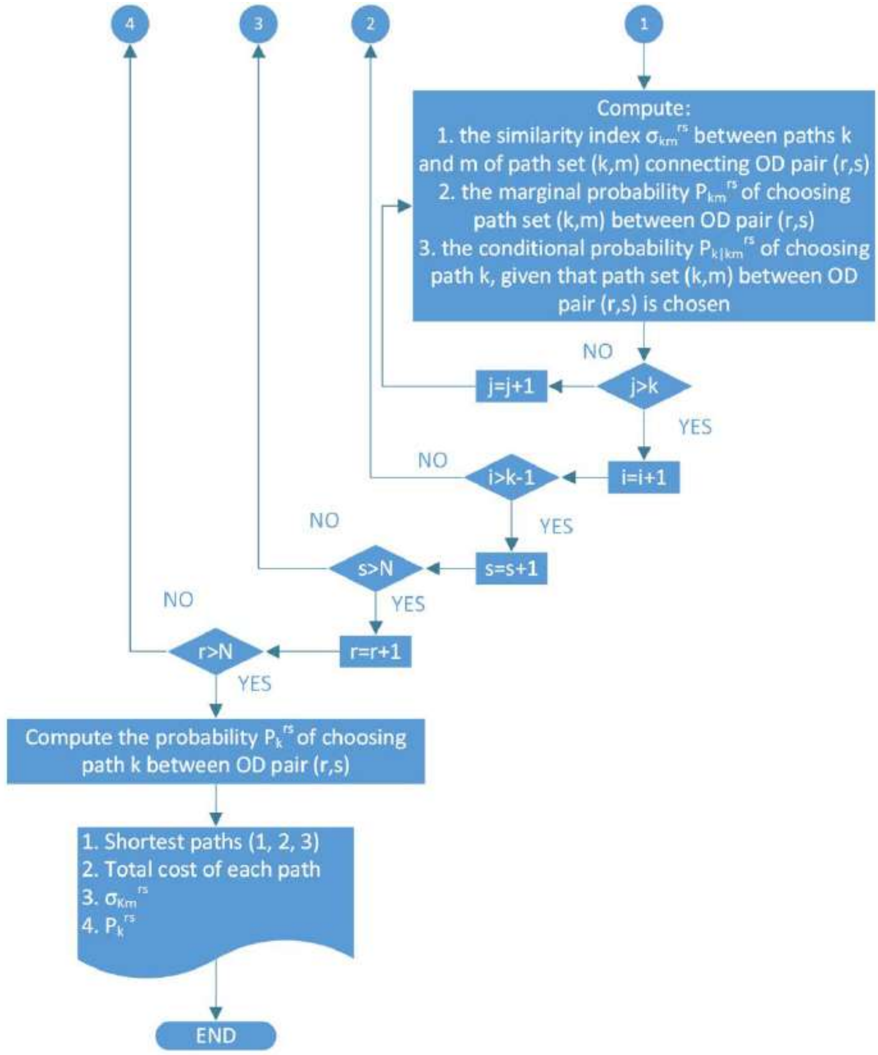


Figure 4.2 Flowchart of the path generation algorithm

5. Solution methodology

5.1 Overview

Real-world problems are generally characterized by a high degree of complexity, as this is indicated by the existence of many parameters affecting the problem formulation along with composite and possibly variable relations between them. Computational complexity, on the other hand, is defined on a three-pillar basis: *problem size*, *algorithm's running time* and *problem reduction* (Eiben & Smith, 2003). Problem size generally refers to the number of participating variables and the range of values these may take. The running time of an algorithm refers to the number of steps needed until termination, with increasing running times for large-scale problems. On that basis, problem hardness can be defined as the relation between problem size and the upper-bound for the worst-case running time, which can be either polynomial or super-polynomial (e.g. exponential), indicating relatively shorter or longer running times respectively. Finally, problem reduction refers to the transformation of a problem into another one through appropriate mapping.

According to their hardness, problems can generally be distinguished into four categories: classes P, NP, NP-complete and NP-hard. Class P comprises the problems for which there exists an algorithm that can solve them within polynomial time. Class NP comprises the problems for which there exists an algorithm that can solve them (irrespective of the running time needed) and any of their solutions can be verified within polynomial time. Class NP-complete comprises the problems that belong to the class NP and any other problem in NP can be reduced to this category by an algorithm running in polynomial time. Finally, class NP-hard comprises the problems which are at least as hard as any problem in the NP-complete class (thus, all NP-complete problems can be reduced to this category) but the solutions cannot necessarily be verified within polynomial time.

Problem hardness can significantly affect the solution methodology followed. For problems belonging to the NP-complete or NP-hard classes, although some small instances may be solved within reasonable computation time, for the rest of the cases optimality cannot be reached and, thus, approximation algorithms or metaheuristics may be needed (Eiben & Smith, 2003). In MNDPs, the discrete variables involved in the problem formulation along with the bi-level structure of the problem result in the non-convexity of the solution space and their classification as NP-hard (Farahani et al., 2013; Xie et al., 2010). Farahani et al. (2013), quoting Ben-Ayed et al. (1988), state that even simple bi-level problems with linear formulations of both the upper- and lower-level sub-problems are NP-hard, while the same authors, quoting Luo et al. (1996), as well as Chootinan et al. (2005) claim that the convexity of bi-level problems cannot be guaranteed even in the case when the individual problems of both levels are convex. MNDP complexity prevents, thus, the use of exact solution algorithms.

Genetic algorithms (GAs) constitute a popular metaheuristic, which is often used in combinatorial optimization problems and has proved to be successful in finding robust solutions within reasonable execution time (Goerigk et al., 2014; Saadatseresht et al., 2009; D' Amico et al., 2002). In this respect, they have been extensively used as a solution methodology in DNDP and MNDP formulations (Farahani et al., 2013). Metaheuristics in general, and GAs in particular, yet possess another trait: the ability to directly handle problem constraints within their algorithmic steps (Farahani et al., 2013). These properties make GAs especially appealing for the problem at hand; for this reason, a GA coupled with a traffic assignment process is employed herein to handle the associated network management problem.

5.2 Genetic algorithms (GAs)

In the following, an overview of the conceptual framework and general function of the GAs under the prism of evolutionary computation is presented. GAs are firstly defined, with description of their main components and mechanisms, explanation of their differences from traditional methods and analysis of the advantages of their use subsequently provided.

5.2.1 Definition

Evolutionary algorithms (EAs), inspired by Darwin's theory of evolution, comprise a set of variants which unfold over the same underlying concept: the mechanism of natural selection (Eiben & Smith, 2003). According to it, given a population of individuals that is compelled to compete in an environment of limited resources, each individual will attempt to dominate over the others to survive. The chances are, however, that only the best individuals will succeed in doing so. This process in known as the *survival of the fittest* and causes the fitness of the population to rise.

Adapting the notion of natural selection to an optimization problem, the solution process goes as follows: An initial set of candidate solutions is first generated and evaluated on the basis of a fitness measure. It is then more possible for the best individuals to be selected as parents to seed the next generation. Reproduction is based on two variation operators, namely recombination and mutation. Whereas recombination is simultaneously applied to two (or perhaps more) selected candidates (parents) to create new solutions (offspring), mutation is applied to one individual at a time to modify it. After having their fitness evaluated, the offspring compete with one another and the previous generation to be selected as part of the new population. The process is repeated until some termination criterion is reached.

As indicated, the pillars of evolutionary progress are the two *variation operators* (*recombination* and *mutation*) and the *selection* process (Eiben & Smith, 2003). Both mechanisms (variation and selection) act in a stochastic manner. The two variation operators create the necessary diversity within the population, guiding the search towards unexplored territories and helping the algorithm to not be trapped in local optima. Selection, on the other hand, generally picks the best solutions derived and, over the generations, leads to an enhancement of the population's fitness.

Genetic algorithms (GAs) are the most widely known type of EAs. They were initially developed in the early 70s' by John Holland and his team at the University of Michigan with a twofold objective (Goldberg, 1989): (a) to conceive and understand the natural systems' adjustment processes, and (b) to develop software that preserves the important mechanisms of those systems. In general, GAs can be defined as search algorithms based on the processes of "natural selection and natural genetics", combining the survival of the fittest with a structured, yet random, information exchange process (Goldberg, 1989). According to the latter, information obtained from previous iterations is used to guide the search towards new points of improved performance. One important trait of the GAs is their high degree of robustness, "the balance between efficiency and efficacy" (Goldberg, 1989), which establishes them as a powerful solution methodology to complex problems.

5.2.2 Components and mechanisms

In order for a GA to be defined, a number of components and mechanisms, suitable for each optimization problem, must be specified. These can be summarized as follows (Eiben & Smith, 2003):

- *Representation (definition of individuals):* Before proceeding with a GA, an appropriate representation of all possible solutions in a computer-applicable form should be established. Solutions in their original form are many times called *candidate solutions*, *phenotypes* or *individuals*, whereas in their encoded form take the names of *chromosomes*, *genotypes* or *strings*. Specific elements of the chromosomes are called *genes*. *Encoding* involves the transformation of a phenotype into a genotype, while the opposite process is called *decoding*. It should be noted that, a phenotype may be very different from its respective genotype, with the algorithm working exclusively within the genotype space.
- *Evaluation (fitness) function:* The fitness function acts as a performance measure during the selection process: assigning a value to each genotype, a respective value in the original problem context can be derived. In GAs, the term *objective function* is additionally used.
- *Population:* In a GA, population stands for the total set of possible solutions (genotypes) present at each generation, with the number of the respective individuals setting the *population size* and the number of different solutions defining its *diversity*. In most applications, the population size remains constant. In addition, the parent selection and replacement mechanisms work at the population level.
- *Parent selection mechanism:* During parent selection, higher-fitness individuals are given priority to be selected as parents to seed the next generation. Due to the probabilistic rules supposed, though, low-fitness individuals are not excluded by the reproduction process; this enables the algorithm to not become trapped in local optima. It can be argued that, along with the replacement mechanism, parent selection is responsible for the over-the-generations enhancement of the solution fitness.

- *Variation operators (recombination and mutation):* The two variation operators are applied to the individuals derived from the parent selection mechanism to generate new solutions. More specifically, during recombination (crossover), two (or more) parent strings are, according to some rule, combined to create offspring. In this way, individuals with different characteristics create solutions that have some probability to combine the best traits of each. In GAs, recombination is the main variation operator, guiding the search to the optimum solution. Its application is stochastic, implying the random switch of genes with the other string of the pair. Mutation, on the other hand, is applied on a single string and it is defined as the occasional (with little probability) change in the value of a gene. In GAs, the role of mutation, although important, is secondary, ensuring population diversity and preventing the possible loss of valuable genes. Similar to recombination, mutation is also a stochastic operator.
- *Survivor selection (replacement) mechanism:* In GAs, since the population size remains almost always constant, the survivor selection (replacement) mechanism distinguishes the best among the preceding (parents) and succeeding (offspring) individuals to create the new generation of solutions. Selection is often deterministic, based on the strings' fitness values (favoring the higher-ranked individuals) or on age (favoring the offspring).

As for the *initialization* and *termination* steps, the initial population is generally generated randomly, although problem-specific heuristics may also be applied to create a population with higher fitness values from the beginning (Eiben & Smith, 2003). In addition, the stochasticity involved in the process implies that optimality may never be reached. As such, other stopping criteria must be set, including, but not limited to, the maximum allowed computational time or the maximum number of iterations.

Last, many optimization problems are subject to constraints which limit the possible solution space and divide it into two regions, a feasible and an infeasible one, containing the set of valid and invalid solutions respectively. As Eiben & Smith (2003) note, *constraint handling* in GAs is achieved through both *direct* and *indirect* techniques. During indirect constraint handling, a penalty is imposed on the fitness value of each solution lying in the infeasible region, with penalties being many times proportional to the number of violated constraints or to some other criterion. In direct constraint handling, on the other hand, infeasible solutions may be discarded from the start or be transformed into feasible ones, or the decoding from the genotype to the phenotype space may be altered so that all solutions in the phenotype space are feasible. However, many problems employ both types of constraint handling simultaneously.

5.2.3 Differences from traditional methods

GAs differ from traditional search and optimization methods in four aspects (Goldberg, 1989):

- *GAs use a coding of the problem's parameters instead of the parameters themselves:* GAs require a set of physical parameters to be coded on a string of finite length with the use of a special alphabet. In Holland's initial algorithm, coding was performed in a binary system but this is no longer necessary.

- *Search takes place at multiple points simultaneously instead of successive investigation of individual points:* Many optimization methods base their search on the successive investigation of individual points in the solution space with the use of some transition rules defined. For functions with multiple optima, however, this point-to-point method can falsely lead to the extraction of a local, instead of a global, optimum. GAs, on the other hand, work on many points simultaneously and, thus, the probability of reaching a local optimum is substantially reduced.
- *Solution assessment is exclusively based on objective function values, and not on derivatives or secondary information:* Based solely on the values of the objective function and excluding the use of any additional information, the flexibility of the GAs can be employed in a variety of problems.
- *Probabilistic, instead of deterministic, transition rules are used:* Probabilistic transition rules are used to guide the search in a random, but directed way, towards territories with increased probability of solution improvement.

5.2.4 Advantages of evolutionary computation

According to Fogel (1997), the advantages of evolutionary computation can be summarized as follows:

- *Conceptual simplicity:* EAs exhibit the trait of conceptual simplicity. After the generation of an initial population of candidate solutions, a new set of offspring is iteratively produced according to the variation operators employed. Solutions are then evaluated and selected on the basis of certain performance criteria, with convergence to the optimal solution gradually achieved. Fogel & Ghozeil (1996) describe the process as:

  $$x\left[t+1\right]=s\left(v\left(x\left[t\right]\right)\right) \tag{5.1}$$

  where $x\left[t\right]$ is the population at time t under representation x, v is a random variation operator and s is the selection operator. The wide range of possible representations, variation operators and selection methods has motivated research on the identification of the optimal algorithmic parameters. It has been proved, though, that there exists neither a unilateral parameter selection for all problems (Wolpert & Macready, 1997), nor a best type of representation for any individual problem (Fogel & Ghozeil, 1997). These facts imply that every optimization problem should be treated as a case per se.
- *Broad applicability:* EAs are practically applicable to any optimization problem (Fogel, 1997). This is due to the fact that the functions to be optimized are not subject to any type of restrictions regarding their form (e.g. continuity hypothesis), the evaluation and selection of the solutions is based solely on the objective function values excluding the need for any additional information (e.g. gradients), and the whole process is independent of the actual solution representation.
- *Improved performance on real problems:* Real-world optimization problems do not always satisfy the conditions posed by classic optimization techniques; for example, they

may exhibit function discontinuity or involve non-linear constraints. In such cases, the complexity of the search space, the possibility of gradient-based methods to be trapped in local optima and the excessive computational time needed in the case of multi-variable problems do not allow for the use of traditional methods. In this context, the EAs can provide an interesting alternative (Schwefel, 1995). These algorithms examine the search space in a random but structured way, making use of already processed information and retaining the best solutions found to generate new ones with even better fitness chances. Nevertheless, the simpler, linear structures are more easily solved with traditional optimization techniques (Bäck, 1996).

- *Possibility of combination with knowledge-specific information and other methods:* In real-world problems, the combination of EAs with knowledge-specific information (in the form of specific variation operators or performance indices) can result in a more efficient exploration of the search space (Fogel, 1997). The EAs can also be combined with more traditional optimization methods in hybrid algorithm forms so as to overcome possible limitations, or with neural networks, fuzzy systems and other program structures to optimize their performance (Fogel, 1997).

- *Feature of parallelism:* Highly complex problems necessitate increased processing power and computational speed, if they are to overcome problem intractability and provide solutions of practical value. The EAs can decrease the required computational time by offering individual, parallel evaluation of possible solutions, with only the comparative selection among them be in need of some serial processing (Fogel, 1997).

- *Robustness to dynamic changes:* As opposed to the EAs, traditional optimization methods lack the ability to dynamically adapt to changes. Whereas the latter may need a complete re-initialization under the new circumstances, the EAs can use the existing population to improve the already formulated solutions (Fogel, 1997). This characteristic is especially desirable when dealing with practical problems.

- *Capability of self-optimization:* Apart from optimizing the objective function value, evolution can also be used to optimize the values of the variables used in the search for the best solution (Fogel, 1997).

- *Ability to automate a problem-solving routine:* According to Fogel (1997), the EAs are capable of doing what human expertise and artificial intelligence have failed to achieve: automate a problem-solving routine. The author argues that, although valuable, human expertise and artificial intelligence are not always applicable, since experts may be apt to error and artificial intelligence has been successfully applied only to domain-specific problems. On the contrary, evolution can be used to learn the fundamental aspects of the systems of interest and acquire problem-solving capabilities.

5.3 GA parameters

Following the order of **Section 5.2.2**, the components and mechanisms involved in the GAs are further analyzed herein, with the individual characteristics assumed for each parameter of the problem at hand described and discussed.

- *Representation (definition of individuals):* As already explained, a proper mapping between the phenotype and genotype spaces is crucial for the successful implementation of the GAs. This representation is highly problem-dependent and, in its simplest form, takes binary values $(0,1)$. Despite its straightforward manner, binary representation may cause problems in phenotype encoding (Eiben & Smith, 2003); for example, if used to represent numbers, the effect of the mutation operator may be variable due to the different significance of the bits. As such, in problems where the phenotypes can more naturally map into genotypes with the use of a discrete space, integer encoding may be a more suitable option (Eiben & Smith, 2003). If continuous variables are additionally present, real-value representation seems to be the best practice (Eiben & Smith, 2003).

  The latter method has been followed in the proposed model; the *number of lanes* y_{ij} along each directed arc (i, j) takes *integer* values, while the *demand adjustment rate* φ^{rs} between each OD pair (r,s) takes *continuous* ones.

- *Evaluation (fitness) function:* In GAs, the fitness of each potential solution is iteratively evaluated, with the evaluation function usually coinciding with the problem's objective one (Eiben & Smith, 2003). This process determines which individuals will comprise each generation; it is, thus, important to proceed with sufficient speed to reduce the computational times involved (Tutorialspoint, 2019a). Where inherent complexities are present (making the original fitness function values hard to be calculated), simple transformations of the objective function and / or other approximations may be used (Eiben & Smith, 2003).

  The present problem uses an *objective function-based evaluation process*. MatLab enables the definition of the fitness function as a separate file, which then serves as input for the main GA function (MathWorks Documentation R2019a, 2019a).

- *Population:* **Figure 5.1** illustrates, in a matrix form, a GA population consisting of M possible solutions (genotypes):

$$\overbrace{\begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,N_{var}} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,N_{var}} \\ \vdots & \vdots & \ddots & \vdots \\ x_{M,1} & x_{M,2} & \cdots & x_{M,N_{var}} \end{bmatrix}}^{number\ of\ variables} \quad \left.\begin{matrix} 1^{st}\ genotype \\ 2^{nd}\ genotype \\ \vdots \\ M^{th}\ genotype \end{matrix}\right\} population$$

Figure 5.1 Matrix representation of a GA population

The number of genes in each genotype equals the number of the problem's decision variables, with the respective array length being, thus, problem-dependent. Population size, on the other hand, remains constant and its selection mechanism aims at retaining a balance between the thorough search of the solution space and the associated computational burden (MathWorks Documentation R2019a, 2019e). The randomly generated initial population is iteratively evolved with the use of variation operators until a solution that meets the desired criteria is found (Eiben & Smith, 2003). In this respect, definition of the population range is critical, since it affects the performance of the GA; while a highly diverse population may hinder the algorithm from reaching convergence, low diversity values can significantly slow down the whole process (MathWorks Documentation R2019a, 2019e).

In the proposed model, (a) the number of lanes y_{ij} along each directed link (i, j), and (b) the demand adjustment rates φ^{rs} between each OD pair (r, s), constitute the problem's decision variables. With N being the number of network nodes, the total number of y_{ij} variables is calculated as $\left(N^2 - N\right)/2$ (**Figure 5.2**), while the respective number of φ^{rs} variables is equal to $\left(N^2 - N\right)$ (**Figure 5.3**). It must be noted that, the lower matrix triangle of y_{ji} variables need not be defined, since for each y_{ij} variable, its accompanying y_{ji} variable is constrained (and, thus, inherently determined) by the initial number of lanes along both link directions.

$$
\begin{array}{c} \\ 1 \\ 2 \\ 3 \\ \vdots \\ N \end{array}
\begin{array}{c}
\begin{array}{cccccc} 1 & 2 & 3 & \cdots & & N \end{array} \\
\begin{bmatrix}
0 & y_{1,2} & y_{1,3} & \cdots & & y_{1,N} \\
0 & 0 & y_{2,3} & \cdots & & y_{2,N} \\
0 & 0 & \ddots & \cdots & & \vdots \\
\vdots & \vdots & \cdots & 0 & & y_{N-1,N} \\
0 & 0 & \cdots & 0 & & 0
\end{bmatrix}
\end{array}
$$

Figure 5.2 Matrix representation of problem's y_{ij} variables (vertical axis: origin node, horizontal axis: destination node)

$$
\begin{array}{c} \\ 1 \\ 2 \\ 3 \\ \vdots \\ N \end{array}
\begin{array}{c}
\begin{array}{ccccc} \mathit{1} & \mathit{2} & \mathit{3} & \cdots & \mathit{N} \end{array} \\
\begin{bmatrix}
0 & \varphi^{1,2} & \varphi^{1,3} & \cdots & \varphi^{1,N} \\
\varphi^{2,1} & 0 & \varphi^{2,3} & \cdots & \varphi^{2,N} \\
\varphi^{3,1} & \varphi^{3,2} & \ddots & \cdots & \vdots \\
\vdots & \vdots & \cdots & 0 & \varphi^{N-1,N} \\
\varphi^{N,1} & \varphi^{N,2} & \cdots & \varphi^{N,N-1} & 0
\end{bmatrix}
\end{array}
$$

Figure 5.3 Matrix representation of problem's φ^{rs} variables (vertical axis: origin node, horizontal axis: destination node)

The initial population is generated by a special, custom-made for mixed integer problems, function developed in MatLab. The *population range* is defined according to the *designated minimum and maximum values for each of the variables*, that is: (a) $\left(0, l_{ij} + l_{ji}\right)$ for y_{ij}, if link (i, j) does not participate in any of the high priority paths, and $\left(1, l_{ij} + l_{ji} - 1\right)$ otherwise, and (b) $\left(\min \text{desired} \, \varphi^{rs}, 1\right)$ for the φ^{rs}. A *random initial population following the uniform distribution* is created, constraining the y_{ij} values to be integer. Although the population size would preferably equal the number of the problem variables, due to the increased computational times needed, the *default population size for mixed integer problems*, as this is defined by MatLab, is selected. This is estimated by (MathWorks Documentation R2019a, 2019c):

$$\min\left(\max\left(10 * NVAR, 40\right), 100\right) \tag{5.2}$$

- *Parent selection mechanism:* Since the genetic imprint of the parents is passed down to their offspring, selection of "good" chromosomes at the mating pool is indispensable for the population fitness to grow over the succeeding generations (Miller & Goldberg, 1995). Different selection mechanisms exist for that purpose (e.g. uniform, stochastic uniform, roulette wheel, tournament etc.), each one exhibiting its own shortcomings and limitations (Eiben & Smith, 2003). In this respect, attention should be paid to the *selection pressure* chosen, that is the degree to which better individuals are favored; a significantly low selection pressure may delay the convergence of the algorithm, while a considerably high one may haste it to a local optimum (Miller & Goldberg, 1995).

  Tournament selection is a strategy based on the organization of successive tournaments between the members of a population. In particular, if N is the desired number of parents and k is the specified tournament size, a total number of N sets of k randomly selected individuals is formed. The k individuals of each set are compared with one another and the one exhibiting the highest fitness value is selected to enter the mating pool (Eiben & Smith, 2003; Miller & Goldberg, 1995). **Figure 5.4** illustrates the flowchart of the process.

Tournament selection is possibly the most widely used selection operator. This may be attributed to its simplicity, but also to the convenience it provides in terms of controlling the selection pressure (Eiben & Smith, 2003). More specifically, a smaller tournament size generally offers a decompression effect since the winner will, on average, have a lower fitness value than the winner of a larger tournament and vice versa (Miller & Goldberg, 1995). Overall, selection of an individual to enter the mating pool depends on the following: (a) its rank in the population, (b) the selected tournament size k, (c) the probability that the most fit member of the tournament is selected (valid only in the case of stochastic processes), and (d) whether the individuals are chosen with replacement or not (Eiben & Smith, 2003).

Tournament selection is the only selection function provided by MatLab for multi-objective GAs (MathWorks Documentation R2019a, 2019d). As such, it was by default used for the problem at hand. **Figure 5.5** presents an indicative example of the tournament selection process for the examined case with a tournament size of $k = 4$.

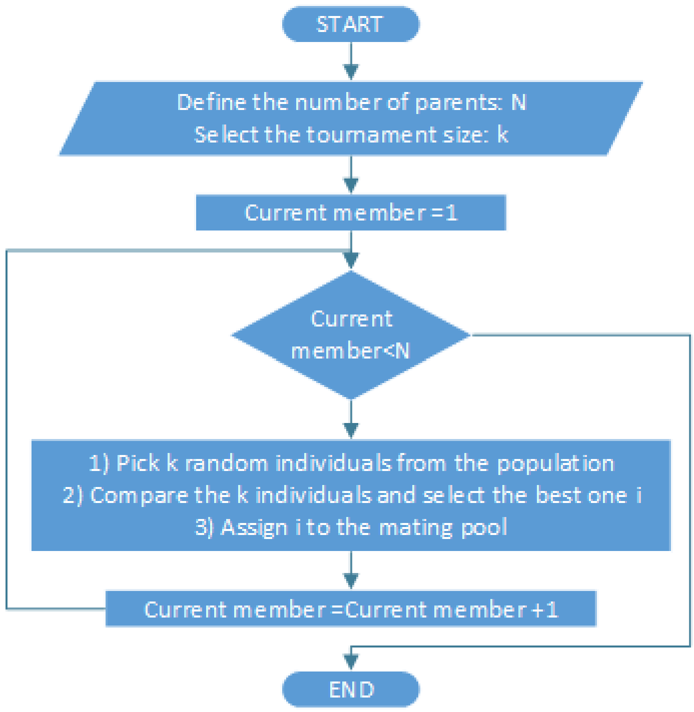


Figure 5.4 Flowchart of the tournament selection process

- *Variation operators (recombination and mutation):* While parent selection determines which individuals will participate in the evolutionary process, the variation operators control the iterative generation of the population. As such, three different types of chromosomes may be distinguished (Eiben & Smith, 2003): (a) those that excelled in the previous generation and are directly transferred into the next one, (b) those that are created through the application of the crossover operator on the individuals comprising the mating pool, and (c) those that come from a single parent who has undergone mutation.

In terms of the first variation operator, crossover may be performed in various ways. The one-point crossover was the first recombination method proposed; the parent chromosomes are divided at a random point and the children inherit one part from the first parent and its supplementary part from the second individual (**Figure 5.6**). A generalization of the previous method is the n-point crossover, in which the parent chromosomes are divided into $n+1$ parts, with each one successively passed down to the offspring (**Figure 5.7**) (Eiben & Smith, 2003). However, these methods are prone to positional bias since they tend to keep the genes that are originally placed next to each other together (Eiben & Smith, 2003). On the other hand, the uniform (or scattered) crossover treats each gene independently, selecting at random the parent it is passed down from (**Figure 5.8**). Nevertheless, despite preventing the transfer of a large number of co-adapted genes (as in the one-point and n-point crossover methods), the uniform crossover method exhibits distributional bias since it tends to transmit an equal share of genes from each parent (Eiben & Smith, 2003). Apart from the discrete recombination methods though, operations based on some sort of weighted average of the parent genes (arithmetic, intermediate or heuristic recombination) have also been proposed (MathWorks Documentation R2019a, 2019d; Eiben & Smith, 2003).

In addition, the most straightforward mutation option is the uniform one (Eiben & Smith, 2003). In this case, the assumed mutation probability defines the fraction of the parent genes that are selected to be replaced by uniformly distributed (in each gene's range), random numbers (MathWorks Documentation R2019a, 2019d). This operation is analogous to a random re-setting in the case of integer encoding (Eiben & Smith, 2003). Yet, another possibility is the non-uniform (Gaussian) mutation: a random number from a Gaussian distribution with zero mean is added to each gene of the parent chromosome (MathWorks Documentation R2019a, 2019d). The standard deviation of the distribution (also called mutation step size) is determined by the initial fluctuation range of each gene (Eiben & Smith, 2003). Finally, the self-adaptive mutation, which uses an iteratively defined step-size according to the success (or not) of the previous generation, has evolved from the previous methods (MathWorks Documentation R2019a, 2019d; Eiben & Smith, 2003).

In the case of multi-objective GAs, MatLab enables all crossover and mutation possibilities (MathWorks Documentation R2019a, 2019d). In the present case, the *uniform option* was selected *for both operators*, with a custom function made for the mutation one. *Three different fractions* of the population (70%, 80%, 90%) are delivered *trough parent recombination*, while *two mutation probabilities* (3%, 5%) are additionally examined.

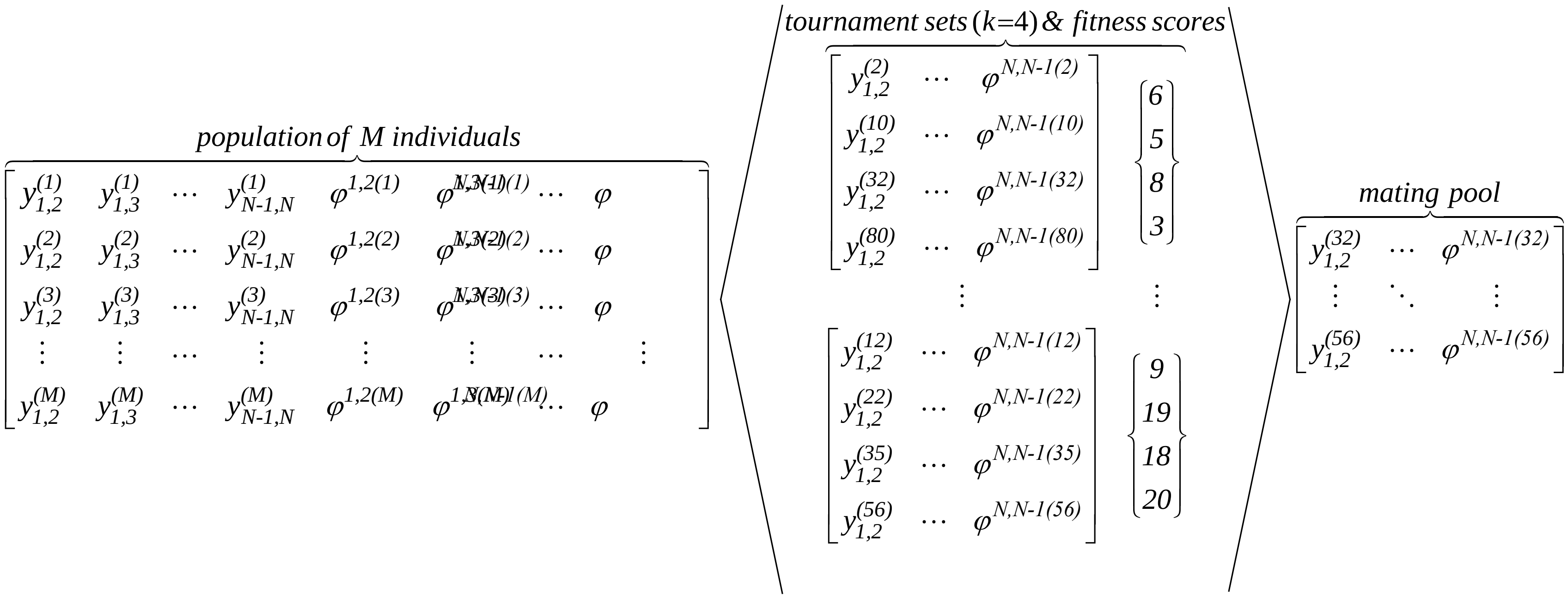


Figure 5.5 Indicative example of the tournament selection process for the examined case (*k=4*)

$$
\begin{array}{l}
y_{1,2}^{(i)} \;\cdots\; y_{m,n}^{(i)} \;\cdots\; \left| y_{N\text{-}1,N}^{(i)} \;\; \varphi^{1,2(i)} \;\cdots\; \varphi^{m,n(i)} \;\cdots\; \varphi^{N,N\text{-}1(i)} \right. \\
y_{1,2}^{(j)} \;\cdots\; y_{m,n}^{(j)} \;\cdots\; \left| y_{N\text{-}1,N}^{(j)} \;\; \varphi^{1,2(j)} \;\cdots\; \varphi^{m,n(j)} \;\cdots\; \varphi^{N,N\text{-}1(j)} \right.
\end{array}
\Rightarrow
\begin{array}{l}
y_{1,2}^{(i)} \;\cdots\; y_{m,n}^{(i)} \;\cdots\; \left| y_{N\text{-}1,N}^{(j)} \;\; \varphi^{1,2(j)} \;\cdots\; \varphi^{m,n(j)} \;\cdots\; \varphi^{N,N\text{-}1(j)} \right. \\
y_{1,2}^{(j)} \;\cdots\; y_{m,n}^{(j)} \;\cdots\; \left| y_{N\text{-}1,N}^{(i)} \;\; \varphi^{1,2(i)} \;\cdots\; \varphi^{m,n(i)} \;\cdots\; \varphi^{N,N\text{-}1(i)} \right.
\end{array}
$$

Figure 5.6 One-point crossover method

$$
\begin{array}{l}
y_{1,2}^{(i)} \; \cdots \; \left| y_{m,n}^{(i)} \; \cdots \; y_{N-1,N}^{(i)} \; \varphi^{1,2(i)} \; \cdots \; \varphi^{m,n(i)} \right| \; \cdots \; \varphi^{N,N-1(i)} \\
y_{1,2}^{(j)} \; \cdots \; \left| y_{m,n}^{(j)} \; \cdots \; y_{N-1,N}^{(j)} \; \varphi^{1,2(j)} \; \cdots \; \varphi^{m,n(j)} \right| \; \cdots \; \varphi^{N,N-1(j)}
\end{array}
\Rightarrow
\begin{array}{l}
y_{1,2}^{(i)} \; \cdots \; \left| y_{m,n}^{(j)} \; \cdots \; y_{N-1,N}^{(j)} \; \varphi^{1,2(j)} \; \cdots \; \varphi^{m,n(j)} \right| \; \cdots \; \varphi^{N,N-1(i)} \\
y_{1,2}^{(j)} \; \cdots \; \left| y_{m,n}^{(i)} \; \cdots \; y_{N-1,N}^{(i)} \; \varphi^{1,2(i)} \; \cdots \; \varphi^{m,n(i)} \right| \; \cdots \; \varphi^{N,N-1(j)}
\end{array}
$$

Figure 5.7 *n*-point crossover method

$$
\begin{array}{l}
\overbrace{\left[\; 0 \; \cdots \; 1 \; \cdots \; 0 \quad 0 \; \cdots \; 1 \; \cdots \; 0 \;\right]}^{binary\,vector} \\
y_{1,2}^{(i)} \; \cdots \; y_{m,n}^{(i)} \; \cdots \; y_{N-1,N}^{(i)} \; \varphi^{1,2(i)} \; \cdots \; \varphi^{m,n(i)} \; \cdots \; \varphi^{N,N-1(i)} \\
y_{1,2}^{(j)} \; \cdots \; y_{m,n}^{(j)} \; \cdots \; y_{N-1,N}^{(j)} \; \varphi^{1,2(j)} \; \cdots \; \varphi^{m,n(j)} \; \cdots \; \varphi^{N,N-1(j)}
\end{array}
\Rightarrow
\begin{array}{l}
y_{1,2}^{(j)} \; \cdots \; y_{m,n}^{(i)} \; \cdots \; y_{N-1,N}^{(j)} \; \varphi^{1,2(j)} \; \cdots \; \varphi^{m,n(i)} \; \cdots \; \varphi^{N,N-1(j)} \\
y_{1,2}^{(i)} \; \cdots \; y_{m,n}^{(j)} \; \cdots \; y_{N-1,N}^{(i)} \; \varphi^{1,2(i)} \; \cdots \; \varphi^{m,n(j)} \; \cdots \; \varphi^{N,N-1(i)}
\end{array}
$$

Figure 5.8 Uniform crossover method

- *Survivor selection (replacement) mechanism:* After the creation of the offspring, the succeeding population has to be determined. This is done by the survivor selection mechanism, which defines the individuals that will pass from the current generation to the next one according to criteria based on either their fitness values or their age (Eiben & Smith, 2003). In this respect, a distinction is made between the *selection* and *replacement* terms on the basis of the number of the newly created children; if the latter exceeds the pre-defined population size, a selection has to take place, otherwise, a number of existing individuals, equal to the number of the generated children, has to be replaced.

  In multi-objective GAs, MatLab proceeds with the *selection process* as follows (MathWorks Documentation R2019a, 2019b): first, the offspring's objective function values are calculated. The children are then mixed with the current population, resulting in an extended one. The rank and crowding distance of all members are computed and the extended population is cut down so as to have the desired size while keeping the appropriate number of individuals at each rank.

In terms of the algorithm's *initialization* process, a GA generally starts with a random initial population, usually represented in a matrix form (MathWorks Documentation R2019a, 2019d). Since the size of the population is critical for the efficiency of the algorithm, a trial and error approach is used for that purpose. Initialization can either be completely random or performed by a known (for the specific problem) heuristic. It has been observed that, while the first case can lead to optimality, the second one may cause low diversity values (Tutorialspoint, 2019b). As a result, an alternative option is the use of some already known good solutions, with the rest of the population generated at random (Tutorialspoint, 2019b).

With MatLab enabling any of the above options (MathWorks Documentation R2019a, 2019d), the *completely random generation of the population* has been selected for the problem at hand.

As for the algorithm's *termination* process, it is easily understood that, despite seeking for the optimal solution, the assumptions and simplifications made during the process imply that, only an approximation of this optimum (albeit with reasonable accuracy) is possible. Even if a certain level of deviation from optimality were to be accepted, the algorithm may have never been able to reach a solution within this range and, thus, the iterative search would continue indefinitely. As such, different stopping criteria have been developed for that purpose. These are generally based on the definition of one of the following (MathWorks Documentation R2019a, 2019c; Eiben & Smith, 2003): (a) the maximum number of generations (specifying the number of iterations performed), (b) the maximum possible running time, (c) the number of generations for which the improvement of the fitness value remains under a certain threshold (in the case of multi-objective GAs, the algorithm stops when the geometric average of the relative change in the spread of Pareto solutions over these generations is less than the threshold value and the final spread is smaller than the average spread), and (d) the time interval with no recorded improvement of the fitness value.

The *first three options* are used in the present case, with MatLab offering all possibilities (MathWorks Documentation R2019a, 2019c). In particular, *the GA stops when one of the* *following criteria is met*: (a) a maximum number of 1,000 generations, (b) a maximum running time of 20,000sec, or (c) the geometric average of the relative change in the spread of Pareto solutions over 100 generations is less than 0.01. These values were defined through trial analyses running for more than 40,000sec.

Finally, the model uses a *direct approach* to treat the *constraints* involved. As illustrated in **Figure 5.9**, for a network with N nodes, a candidate solution is formed with a total of $\left(N^2-N\right)/2$ integer decision variables $\left(y_{ij}\right)$ and $\left(N^2-N\right)$ continuous ones $\left(\varphi^{rs}\right)$.

$$\left[y_{1,2}^{(j)} \quad \cdots \quad y_{m,n}^{(j)} \quad \cdots \quad y_{N\text{-}1,N}^{(j)} \quad \varphi^{1,2(j)} \quad \cdots \quad \varphi^{m,n(j)} \quad \cdots \quad \varphi^{N,N\text{-}1(j)}\right],\ 1 \le j \le population\, size$$

Figure 5.9 Representation of problem's candidate solutions

Certain constraints apply to the different types of genes, though. More specifically, *the value of* y_{ij} depends on the initial number of existing lanes along both link directions. *Two cases* can be distinguished in this respect: when link (i, j) participates in a high priority path, at least one lane must be designated per direction, that is:

$$1 \le y_{ij} \le l_{ij} + l_{ji} - 1 \qquad (5.3)$$

otherwise, it applies that:

$$0 \le y_{ij} \le l_{ij} + l_{ji} \qquad (5.4)$$

As for *the demand adjustment rate* φ^{rs}, its value range is specified as:

$$\min desired\, value \le \varphi^{rs} \le 1 \qquad (5.5)$$

Apart from the variables' upper and lower bounds, however, *additional constrains* are required to ensure the *connectivity of the network*. As such, **Figure 5.10** illustrates the number of lanes emanating from node i and heading towards node j, when lane reversal is employed.

$$\begin{array}{c} \\ 1 \\ 2 \\ 3 \\ \vdots \\ N \end{array} \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & \cdots & N \end{array} \\ \begin{bmatrix} 0 & y_{1,2} & y_{1,3} & \cdots & y_{1,N} \\ l_{1,2}+l_{2,1}-y_{1,2} & 0 & y_{2,3} & \cdots & y_{2,N} \\ l_{1,3}+l_{3,1}-y_{1,3} & l_{2,3}+l_{3,2}-y_{2,3} & \ddots & \cdots & \vdots \\ \vdots & \vdots & \cdots & 0 & y_{N-1,N} \\ l_{1,N}+l_{N,1}-y_{1,N} & l_{2,N}+l_{N,2}-y_{2,N} & \cdots & l_{N-1,N}+l_{N,N-1}-y_{N-1,N} & 0 \end{bmatrix} \end{array}$$

Figure 5.10 Matrix representation of the links entering and exiting each network node in the case lane reversal is employed (vertical axis: origin node, horizontal axis: destination node)

On that basis, and in order for the connectivity condition to hold, there must exist at least one lane entering and one lane exiting each node. This implies that, the sum of the lanes in each column and row of the table has to exceed one. The restrictions are delineated as follows:

$$
\begin{gathered}
y_{1,2} + y_{1,3} + \cdots + y_{1,N} > 1 \\
l_{1,2} + l_{2,1} - y_{1,2} + y_{2,3} + \cdots + y_{2,N} > 1 \\
\vdots \\
l_{1,N} + l_{N,1} - y_{1,N} + l_{2,N} + l_{N,2} - y_{2,N} + \cdots + l_{N\text{-}1,N} + l_{N,N\text{-}1} - y_{N\text{-}1,N} > 1 \\
\\
l_{1,2} + l_{2,1} - y_{1,2} + l_{1,3} + l_{3,1} - y_{1,3} + \cdots + l_{1,N} + l_{N,1} - y_{1,N} > 1 \\
y_{1,2} + l_{2,3} + l_{3,2} - y_{2,3} + \cdots + l_{2,N} + l_{N,2} - y_{2,N} > 1 \\
\vdots \\
y_{1,N} + y_{2,N} + \cdots + y_{N\text{-}1,N} > 1
\end{gathered}
\tag{5.6}
$$

6. Application and case studies

6.1 Overview

In order to test, and ultimately verify, the ability of the proposed model to improve network functionality in the aftermath of a catastrophic event, a test network is used as the basis for a series of analyses to be performed. The OD-pair demand (which is kept the same across most of the analyses) is randomly generated according to a uniform distribution, with upper and lower bounds restricting its possible value range. In total, a set of 1620 analyses are conducted. These can be distinguished into *four* categories, according to the differentiating parameter each time involved: (a) changes in the *network's physical attributes*, including changes in network topology (disruption of network nodes and links) and link capacity, (b) modifications of *problem parameters*, including changes in the values of the penalty factor P (involved in the path generation process) and the dispersion coefficient θ (indicating the variance among the drivers and involved in the SUE model), complemented, in the latter case, with analyses performing a deterministic assignment of traffic on the network links according to the DUE and the system optimal (SO) principles, (c) fluctuations of the *demand* between the network's OD pairs, and finally, (d) variations of the *weighting coefficients* of the upper-level objective function terms (sensitivity analysis). In this respect, the goal is twofold: (a) to investigate the algorithm's efficiency and efficacy in enhancing network performance, and (b) to explore the implicit relationship between the problem's optimal solution and the aforementioned changes in the problem's input parameters.

6.2 Preliminary steps

Before proceeding with the analyses, the subsequent sections analyze some of the primary data involved. These regard the description of the test network, where the model is applied on, and the determination of the OD-pair demand volumes.

6.2.1 Network description

The proposed framework is applied on a test network with fifteen nodes and forty eight links. The network provides the necessary background to: (a) investigate the model's ability to enhance network functionality, and (b) examine the influence of various parameters on the achieved network performance. The configuration of the network is illustrated in **Figure 6.1**, with its topological attributes summarized in **Table 6.1**. In this network, nodes *2* and *11* are considered to be the special importance ones (subset N_{sp}); it is reminded that these correspond to facilities which are vital for population safety, community restoration and continuation of activities (for example, node *2* could correspond to the city's hospital and node *11* to the police station). Nodes *5* and *14* constitute the other end of the N_{sp} node pairs, between which are formed the high priority paths; that is, paths serving node pairs $(2-5)$, $(5-2)$, $(2-14)$, $(14-2)$, $(11-5)$, $(5-11)$, $(11-14)$ and $(14-11)$ are excluded from the possibility of contraflow operations and there must be at least one lane ensured per direction. Paths connecting all other OD-pairs (low priority paths) are not subjected to this type of restriction, thus, contraflow operations may be applied.

6.2.2 OD-pair demand

The initial, non-adjusted demand between each of the network's OD pairs is randomly created according to the uniform distribution, with upper and lower bounds set on the derived q^{rs}. In this respect, the generated demand matrix is provided in **Table 6.2**, with q^{rs} values lying within the [100, 250] interval.

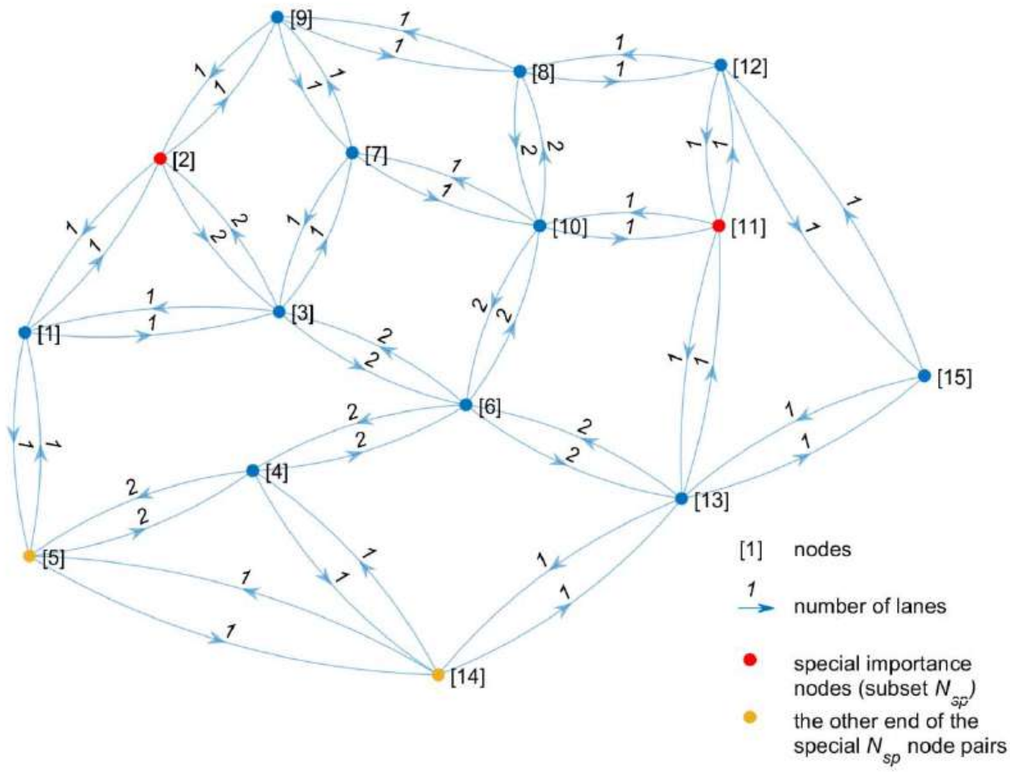


Figure 6.1 Configuration of the *15*-node test network

Table 6.1 Topological attributes of the test network

Start node	End node	Number of lanes	Length (m)
1	2	1	470.95
1	3	1	542.08
1	5	1	480.09
2	1	1	470.95
2	3	2	414.53
2	9	1	392.54
3	1	1	542.08
3	2	2	414.53
3	6	2	445.83
3	7	1	374.57
4	5	2	509.88
4	6	2	474.79
4	14	1	589.69
5	1	1	480.09
5	4	2	509.88
5	14	1	906.4
6	3	2	445.83
6	4	2	474.79
6	10	2	414.9
6	13	2	500.89
7	3	1	374.57
7	9	1	332.1
7	10	1	428.4
8	9	1	528.43
8	10	2	333.9
8	12	1	427.54
9	2	1	392.54
9	7	1	332.1
9	8	1	528.43
10	6	2	414.9
10	7	1	428.4
10	8	2	333.9
10	11	1	380.27
11	10	1	380.27
11	12	1	344.43
11	13	1	589.71
12	8	1	427.54
12	11	1	344.43
12	15	1	794.76
13	6	2	500.89
13	11	1	589.71
13	14	1	641.52
13	15	1	579.33
14	4	1	589.69
14	5	1	906.4
14	13	1	641.52
15	12	1	794.76
15	13	1	579.33

Table 6.2 OD-pair demand on the test network

q^{rs}	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	208	124	135	153	240	164	139	224	172	134	125	130	165	177
2	140	0	177	185	230	157	141	228	176	129	222	142	241	243	160
3	247	217	0	245	153	219	224	190	239	151	171	205	221	234	240
4	245	171	220	0	226	218	160	250	143	136	151	215	183	192	176
5	183	205	224	196	0	169	189	130	154	144	172	204	177	201	144
6	224	142	144	149	241	0	141	177	139	151	132	179	178	196	238
7	138	212	184	218	165	129	0	133	137	174	137	191	160	147	248
8	175	124	178	153	145	127	154	0	233	126	243	158	186	159	177
9	239	156	204	186	152	189	205	120	0	238	245	217	186	181	134
10	223	126	212	211	200	222	210	221	192	0	195	144	227	150	153
11	245	132	218	236	182	242	218	227	138	184	0	209	224	230	173
12	205	227	156	245	166	137	179	233	231	184	150	0	204	145	197
13	124	211	209	191	228	194	130	131	201	164	166	168	0	149	154
14	231	161	205	138	196	181	149	172	165	237	227	201	226	0	198
15	242	244	141	139	192	121	239	154	187	168	122	222	189	149	0

6.3 Results

Analyses on the test network are based on scenario formulations, exploring how perturbations of the problem parameters affect the expected outcome. Thirty runs (Papoulis, 1991) for each of the six combinations of mutation and crossover parameters are carried out per case, resulting in a total of one hundred and eighty analyses for each of the examined scenarios when changes in: (a) the network's physical attributes, (b) parameters P and θ, and (c) the OD-pair demand are assumed. The same also applies to the analyses which perform a deterministic assignment of traffic on the network (DUE and SO models). As for the sensitivity analyses conducted, these also rise up to the number of one hundred and eighty, with thirty runs performed for each of the six combinations of the weighting coefficients of the upper-level objective function terms. **Table 6.3** summarizes the distinct scenarios examined per parameter considered, with references to the tables where the respective analysis results are found. Unless otherwise referenced, in all the analyses, speed on the network links is assumed to be uniform and equal to 50km/h, the BPR function parameters are equal to $m_2 = 0.15$ and $m_3 = 4$, the q^{rs} values are those outlined in **Table 6.2**, parameters P and θ both take the value of 0.1, parameter α is taken as $\alpha = 0.5$, and the three weighting coefficients (w_1, w_2, w_3) are assumed to be equal to 1/3. All analyses were run on an Intel (R) Core (TM) i7 processor - 6700 CPU (3.40GHz) with 16GB of RAM.

Table 6.3 Scenarios examined

Parameter	Scenario
Network's physical attributes (complete and partial component failures)	Base case scenario (*15*-node network with c_{ij} = 900 veh/h/lane) (**Table 6.4**)
	Link capacity degradation scenario (*15*-node network with c_{ij} = 500 veh/h/lane) (**Table C.1**)
	Complete component failure scenario (*14*-node network with c_{ij} = 900 veh/h/lane) (**Table C.2**)
Problem parameters (variance among drivers and path generation process)	Increased level of stochasticity scenario (*15*-node network with c_{ij} = 900 veh/h/lane and θ = 0.01) (**Table C.3**)
	DUE analysis (*15*-node network with c_{ij} = 900 veh/h/lane) (**Table C.4**)
	SO analysis (*15*-node network with c_{ij} = 900 veh/h/lane) (**Table C.5**)
	Increased path dissimilarity scenario (*15*-node network with c_{ij} = 900 veh/h/lane and P = 0.5) (**Table C.6**)
Demand	Demand augmentation scenario (*15*-node network with c_{ij} = 900 veh/h/lane and $q^{rs'} = 2.0q^{rs}$) (**Table C.7**)
Sensitivity analysis	Six combinations of the (w_1, w_2, w_3) weighting factors (*15*-node network with c_{ij} = 900 veh/h/lane) (**Table 6.12**)

6.3.1 Changes in the network's physical attributes

The *15*-node network with link capacity equal to $c_{ij} = 900 veh/h/lane$ constitutes the base case scenario for the problem at hand. Two additional case studies are examined. The first one refers to the link capacity degradation scenario; this unfolds over the *15*-node network, assuming a link capacity of $c_{ij} = 500 veh/h/lane$. This scenario corresponds to catastrophes that can partially (in terms of the capacity potential) impair the network, either entirely (all links are imposed to the capacity decrease), or to a certain extent (only some of the links experience the reduction). Phenomena leading to such network conditions may extend from flood events and earthquake debris accumulation on the roadside, to cars parked along the network links. In the respective scenario, all links are assumed to suffer capacity reduction. The second case study considers the complete failure of a network node and its subsequent removal from the network configuration along with its associated links (links entering or exiting that node). This scenario implies a change in the network's connectivity settings and is indicative of a pinpointed catastrophe, because of which access is restricted to a particular area. In this case, node *4* is assumed to be the one impacted, with all links having one of their ends at this node removed from the network. As a result, the final, post-disaster network in this case is composed of fourteen nodes and forty two links (**Figure 6.2**).

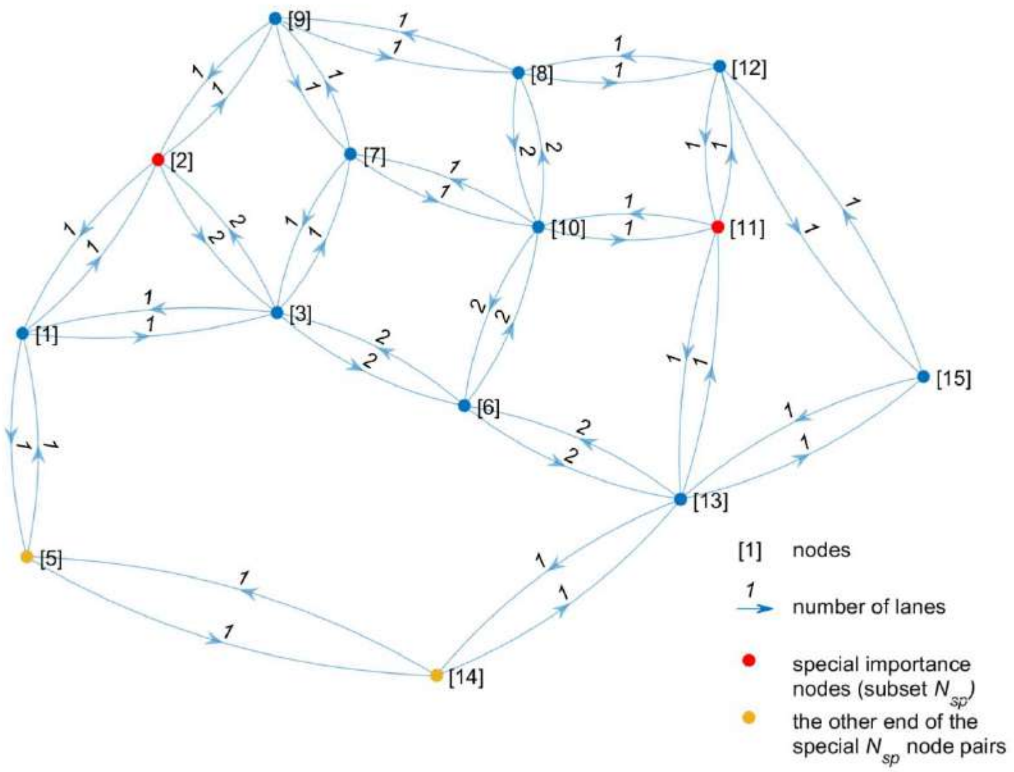


Figure 6.2 Configuration of the *14*-node test network

In this respect, **Table 6.4** summarizes the results for the base case scenario (*15*-node network, $c_{ij} = 900veh/h/lane$). The table presents the objective function (OF) value best runs for each of the six combinations of crossover and mutation rates (CR and MR respectively), also broken down into the individual values of the TNTT, SD and OD-A components. Average OF values for each of the CR / MR combinations (thirty runs), along with the average value of all the analyses conducted (one hundred and eighty runs) are provided in the table's last column. The respective average OF and OF component values for the best runs, along with the standard deviation and the coefficient of variation that each of the terms exhibit are additionally calculated. Finally, for the absolutely best experiment, the OF and OF terms' deviation from the average are computed as well. The respective results for the *15*-node network $\left(c_{ij} = 500veh/h/lane\right)$ and the *14*-node network $\left(c_{ij} = 900veh/h/lane\right)$ are provided in Appendix C.

From **Table 6.4**, it can be observed that, for the base case scenario, the CR / MR combination that corresponds to the best experiment (minimum OF value) is that of 0.80 / 0.05, with the respective best OF value being equal to 0.045511. Comparing the results of all CR / MR best runs, it can be concluded that the absolutely best OF value is driven by the lowest distance-based OD-A component obtained (equal to 0.247505). In addition, the average OF value of the CR / MR best runs is 0.076034, with the mean OF value of all runs being 0.137125, while the associated coefficients of variation are calculated as 28.89% and 7.15% respectively. The increased coefficient value in the first case may be attributed to the limited number of analyses considered (six analyses, as is the number of the CR / MR combinations), while it drops in the second case where all the analyses are involved (one hundred and eighty runs). Furthermore, the OF term that exhibits the lowest coefficient of variation is the SD value (1.28%), followed by the distance-based OD-A component (6.85%). On the other hand, the terms exhibiting the highest coefficient of variation are the ones related to travel time (TNTT (13.06%) and travel time-based OD-A (12.97%)). In this respect, the model appears to be more sensitive to the problem's travel time aspect (in its various forms) than it is to the demand parameter or to the length of the paths constructed, which remain relatively stable throughout the analyses. It must be noted, though, that the closest the mean value of each OF term is to zero, the more sensitive the respective coefficient of variation is bound to be, even to small changes of the mean. As such, the higher coefficients of variation exhibited by the travel time-related components can be attributed to their low mean values. Overall, the OF coefficient of variation of all runs is calculated as 7.15%, which is relatively low, indicating the robustness of the model in producing consistent results.

Figure 6.3 focuses on the best CR / MR combination and the optimal solution for the base case scenario. More specifically, with the best combination being that of 0.80 / 0.05, **Figure 6.3(a)** presents the respective combination runs, while **Figure 6.3(b)** presents the absolutely best run, along with the combination's average OF value μ, accompanied with the average value μ plus or minus the combination's standard deviation σ $\left(\mu+\sigma, \mu-\sigma\right)$. Afterwards, **Figure 6.3(c)** illustrates the network's optimal lane configuration for the scenario examined. From **Figure 6.3(a)**, it can be concluded that all combination runs tend to reach their ultimate OF value approximately after the 20^{th} generation, with the runs' OF values lying relatively close to one another. This fact implies that, without any constraint relaxation, a reasonably good solution to the problem could be obtained in about 1/5 of the computational time used in the present case (i.e. in approximately 55min). In addition, as outlined in **Table 6.4** and illustrated in **Figure 6.3(b)**, the best OF value lies relatively low, indicating the algorithm's efficiency in achieving improved network performance. Finally, as displayed in **Figure 6.3(c)**, the proposed network configuration meets all the criteria set, ensuring network's connectivity as well as the existence of at least one lane per direction between the network's node pairs that are connected with high priority paths (that is, between node pairs $(2-5)$, $(5-2)$, $(2-14)$, $(14-2)$, $(11-5)$, $(5-11)$, $(11-14)$ and $(14-11)$). Besides that, the algorithm proves to make extensive use of the lane reversal strategy, with an adequate number of roads also turning to one-way streets.

Table 6.5 summarizes: (a) the average of all runs OF value for the best CR / MR combination (i.e. the combination corresponding to the best experiment) (thirty analyses), and (b) the average

OF value of all the runs conducted (one hundred and eighty analyses) for: (a) the *15*-node network with $c_{ij} = 900 veh / h / lane$ (base case scenario), (b) the *15*-node network with $c_{ij} = 500 veh / h / lane$, and (c) the *14*-node network with $c_{ij} = 900 veh / h / lane$. The table calculates: (a) the deviation of the best CR / MR runs' mean from the average value of all runs for each individual scenario, and (b) the deviation of those terms for the second and third case studies from the respective values of the base case one. From **Table 6.5**, it can be concluded that, in all three experiments, the deviation of the best CR / MR runs' average from the overall mean value remains relatively low (-9.76%, 1.21% and 4.06% for the three cases respectively), indicating the robustness of the algorithm in producing consistent results. Moreover, for the second scenario, the deviation of the best CR / MR combination's average from the base case one is calculated as 14.19%, while the respective value for all runs drops to 1.81%. For the *14*-node network scenario, the corresponding deviations are equal to 20.67% and 4.64%. The results indicate that a deterioration of the network's link capacity and / or a failure of its nodes and links result in a decrease of its performance; the latter appears to be greater in the case of complete failures (third scenario) as in the case of partial ones (second case study). This fact accentuates the importance of retaining network's connectivity under all circumstances. It must be noted that the smaller deviations observed when the average of all runs is considered are due to the larger number of analyses incorporated in the sample (one hundred and eighty analyses as opposed to thirty).

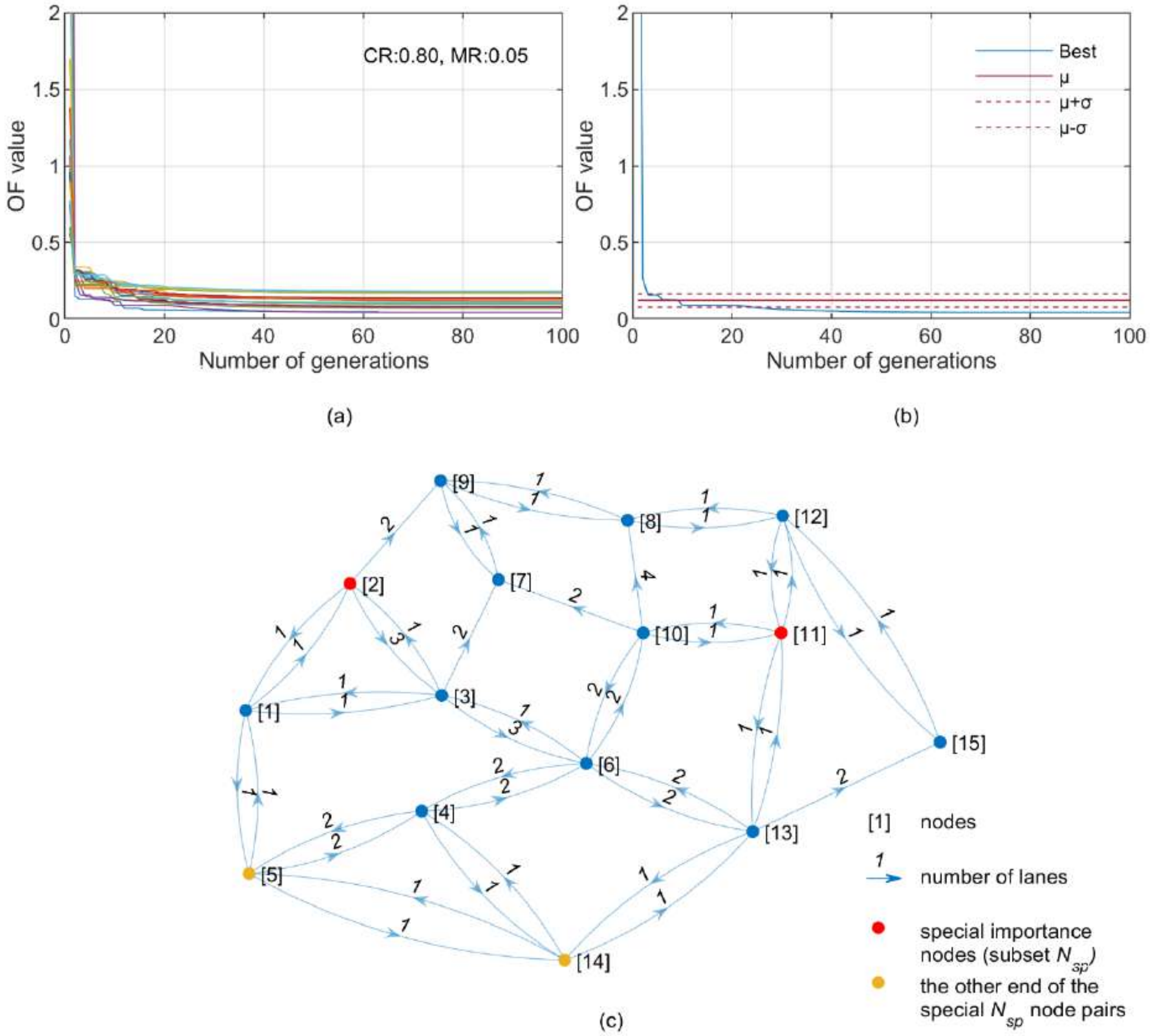


Figure 6.3 Best CR / MR combination for the *15*-node network with c_{ij} = 900veh/h/lane: (a) OF values of all the combination runs, (b) best-run OF, μ, μ+σ and μ-σ values, (c) lane configuration for the best run

Table 6.4 Analysis results for the *15*-node network with c_{ij} = 900veh/h/lane

	Crossover rate	Mutation rate	Objective function best runs					Objective function (average of all runs)
			Total network travel time	Satisfied demand	OD-pair accessibility		Objective function	
					Distance-based	Travel time-based		
15 nodes, c_{ij} = 900veh/h/lane	0.70	0.03	0.013732	0.248772	0.259763	0.024406	0.049129	0.145649
	0.80	0.03	0.015332	0.241088	0.300090	0.030761	0.105095	0.153223
	0.90	0.03	0.013859	0.242975	0.295036	0.025616	0.091537	0.137182
	0.70	0.05	0.016551	0.241455	0.285897	0.027477	0.088471	0.132584
	0.80	**0.05**	**0.018254**	**0.248638**	**0.247505**	**0.028390**	**0.045511**	**0.123745**
	0.90	0.05	0.012345	0.244422	0.288507	0.020031	0.076461	0.130365
	Average		0.015012	0.244558	0.279466	0.026114	0.076034	**0.137125**
	Standard deviation		0.001960	0.003125	0.019151	0.003386	0.021967	0.009808
	Coefficient of variation (%)		13.058287	1.277942	6.852720	12.967229	28.891069	7.152491
	Best experiment		0.018254	0.248638	0.247505	0.028390	0.045511	na
	Deviation from average (%)		21.591789	1.668294	-11.436488	8.717580	-40.144171	na

Table 6.5 OF results: (a) *15*-node network with c_{ij} = 900veh/h/lane, (b) *15*-node network with c_{ij} = 500veh/h/lane, and (c) *14*-node network with c_{ij} = 900veh/h/lane

	Objective function			Deviation from the base case scenario (%)	
	15 **nodes, c_{ij} = 900veh/h/lane**	***15*** **nodes, c_{ij} = 500veh/h/lane**	***14*** **nodes, c_{ij} = 900veh/h/lane**	***15*** **nodes, c_{ij} = 500veh/h/lane**	***14*** **nodes, c_{ij} = 900veh/h/lane**
Average of all runs for the best CR / MR combination	0.123745	0.141306	0.149323	14.191280	20.669926
Average of all runs	0.137125	0.139611	0.143491	1.812944	4.642479
Deviation from the average of all runs (%)	-9.757521	1.214088	4.064366	na	na

Figure 6.4 provides an illustrative representation of: (a) the best, and (b) the average of all runs OF values for the three case studies examined. As illustrated in **Figure 6.4**, both the best and the average values maintain the same hierarchical sequence between the experiments, with the base case scenario providing the lowest values of all, followed by the scenario of link capacity degradation and then the scenario of complete component failure. It can be observed that the model, despite not being able to compensate for the initial deterioration of the network's operative features in order for them to reach the base case scenario, proves to be equally effective in enhancing network performance across all the case studies examined (the experiments reach almost the same normalized OF value, either in its best or in its mean form).

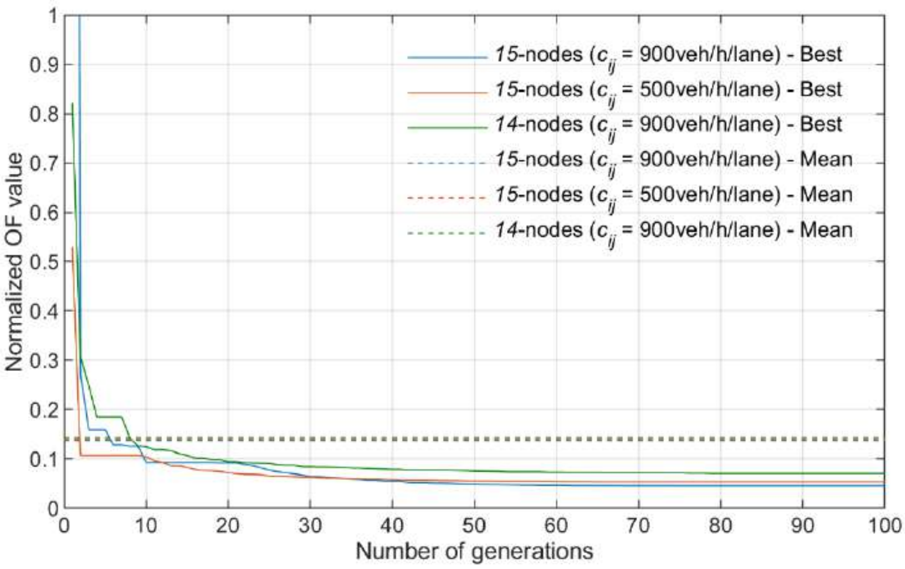


Figure 6.4 Best and average (of all runs) OF values: (a) *15*-node network with c_{ij} = 900veh/h/lane, (b) *15*-node network with c_{ij} = 500veh/h/lane, and (c) *14*-node network with c_{ij} = 900veh/h/lane

Figure 6.5 illustrates in a three axis form (TNTT, SD, OD-A) the results of all the analyses conducted (one hundred and eighty runs per case) for the: (a) the *15*-node network with $c_{ij} = 900veh/h/lane$ (**Figure 6.5(a)**), (b) the *15*-node network with $c_{ij} = 500veh/h/lane$ (**Figure 6.5(b)**), and (c) the *14*-node network with $c_{ij} = 900veh/h/lane$ (**Figure 6.5(c)**). Along with the results of the best runs provided in **Table 6.4** for the base case scenario and in Appendix C for the other two case studies, the 3D representation of the results of all runs depicted in **Figure 6.5** provides an overview of the whole analysis course. It also helps gain greater insight into the way the three individual terms of the upper-level OF are combined with one another and ultimately contribute to the formulation of the respective results. Finally, the 3D display of the solution space helps conceptualize the location of each one of the solutions in relation to the rest ones present, perhaps leading to the choice of a different (rather than the absolutely OF optimal) result on the basis of certain criteria.

As such, **Figures 6.5(a), 6.5(b)** and **6.5(c)** demonstrate the existence of two clusters of solutions per case. In order to help interpret this configuration and despite the differences between the respective OF terms' values being either way small, **Table 6.6** calculates the mean TNTT, SD, OD-A and OF cluster values for each one of the experiments. From **Table 6.6** and **Figure 6.5** it can be concluded that, in all cases, the two clusters are indicative of two distinct types of solutions; more specifically, the first cluster (the left one) generally corresponds to solutions exhibiting lower TNTT and higher SD values, while for the second cluster (the right one) the opposite is valid. The first cluster also exhibits lower OD-A values (higher accessibility) driven by the lower distance and travel time components involved, with the distance-based component remaining significantly higher than the respective travel time-based one in all cases. It is also important to notice that the lower travel time values and the higher accessibility values and satisfied demand rates achieved in the first set of solutions generally lead the best experiments of all CR / MR combinations to belong to this cluster (**Figures 6.5(a), 6.5(b)** and **6.5(c)**).

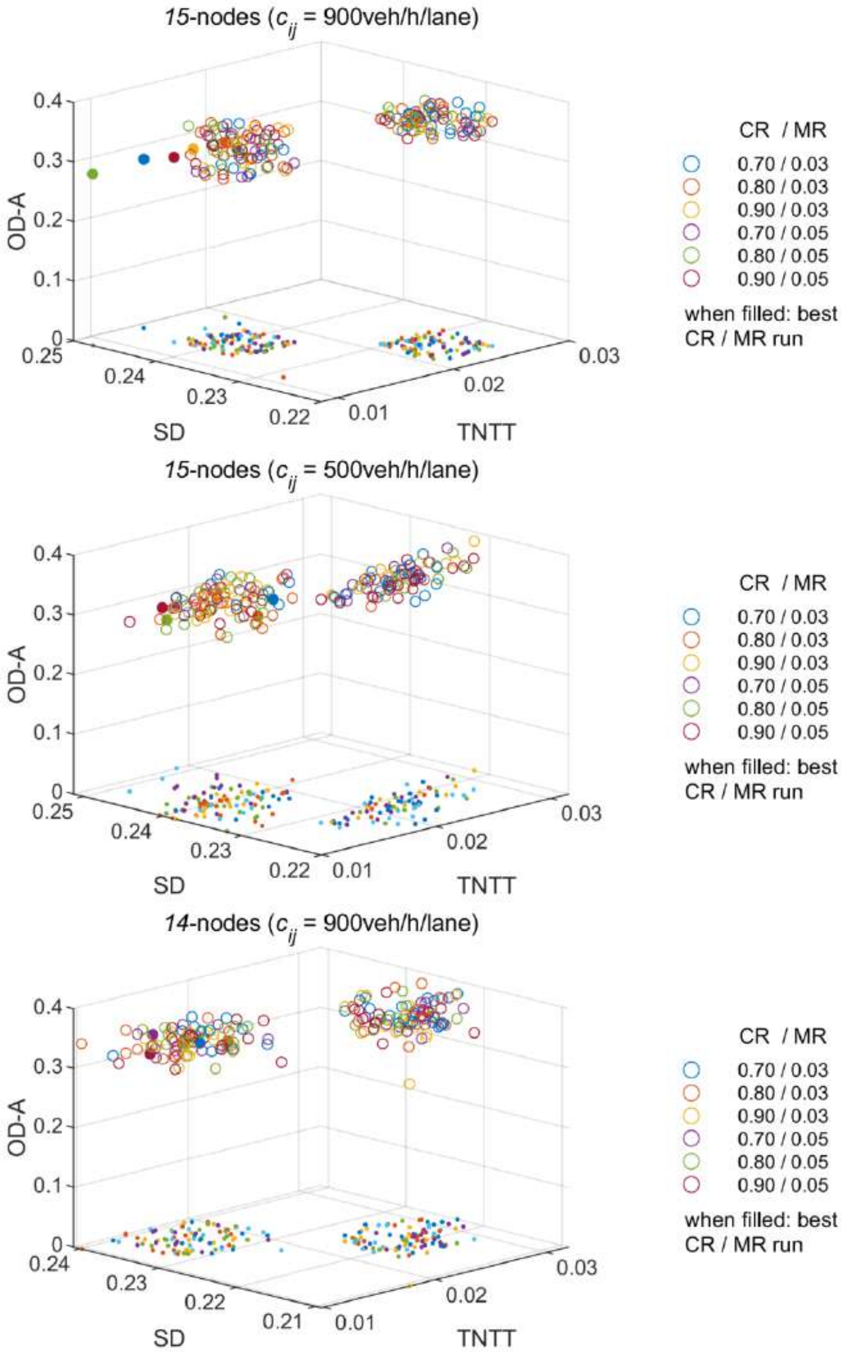


Figure 6.5 The results of all runs in a three-axis form (TNTT, SD, OD-A): (a) *15*-node network with c_{ij} = 900veh/h/lane, (b) *15*-node network with c_{ij} = 500veh/h/lane, and (c) *14*-node network with c_{ij} = 900veh/h/lane

Table 6.6 Mean cluster OF and OF terms' values: (a) *15*-node network with c_{ij} = 900veh/h/lane, (b) *15*-node network with c_{ij} = 500veh/h/lane, and (c) *14*-node network with c_{ij} = 900veh/h/lane

	Mean cluster values				
	Total network travel time	Satisfied demand	OD-pair accessibility		Objective function
			Distance-based	Travel time-based	
***15*-nodes, c_{ij} = 900veh/h/lane**					
1st cluster	0.014845	0.240405	0.308249	0.027528	0.110217
2nd cluster	0.022427	0.228738	0.337330	0.039034	0.170054
***15*-nodes, c_{ij} = 500veh/h/lane**					
1st cluster	0.015154	0.239814	0.307233	0.027496	0.110069
2nd cluster	0.022020	0.227941	0.340747	0.038072	0.172896
***14*-nodes, c_{ij} = 900veh/h/lane**					
1st cluster	0.016284	0.234714	0.303207	0.029533	0.114312
2nd cluster	0.025934	0.221487	0.332194	0.042993	0.179633

In addition, **Figure 6.6** presents, for the base case scenario, the relative lane-changing frequency of each of the network's links. Lane-changing frequency here refers to how often a link undergoes changes with respect to the number of lanes it possesses, by losing lanes to or gaining lanes from the opposite direction link. In this respect, lane-changing frequency acts as a measure of the link's criticality in the final network configuration, with higher frequencies indicating higher criticality. For illustrative purposes, the figure is divided into two parts: the first part (**Figure 6.6(a)**) corresponds to the links of one direction $\left((i,j),\forall i<j\right)$, with the second image (**Figure 6.6(b)**) depicting the links of the opposite one. The colors of the vertical bars along the links indicate the number of lanes that a link loses to or gains from the other direction, while their height represents the respective relative frequency this happens. As such, the blue bars imply that a link loses two lanes to the opposite direction and the red ones that a link is minus one lane. On the other hand, the green bars indicate that a link gains two lanes from the other direction, while the orange ones illustrate that a link is plus one lane.

In this respect, link $(7,10)$ appears to be the most critical link of the network, with a cumulative (including all types of changes, $(\pm 1, \pm 2)$) relative lane-changing frequency of 91.67% (**Table C.8**). As expected, its other-direction link $(10,7)$ exhibits the same frequency as well. Apart from link $(7,10)$, though, other critical network links are (in a descending order of cumulative relative frequency) the following: links $(8,10)$, $(11,12)$, $(13,15)$, $(8,12)$, $(3,7)$, and so on. The results, illustratively depicted in terms of the relative frequency in **Figure 6.6**, are analytically provided in Appendix C.

However, since the two clusters of solutions of **Figure 6.5(a)** correspond to results of distinct quality, closer attention is paid to distinguish any special characteristics of the two groups. As such, **Figure 6.7** is analogous to **Figure 6.6**, but instead of referring to the whole number of analyses conducted (one hundred and eighty runs), it only refers to the solutions belonging to the first set of results of **Figure 6.5(a)**. The same also applies to **Figure 6.8** with respect to the second set. In addition, **Tables 6.7** and **6.8** summarize the mean φ^{rs} values achieved by the solutions belonging to both the first and the second solution sets respectively.

Comparing **Figure 6.7** with **Figure 6.8**, it can be observed that the relative lane-changing frequency of the first cluster (**Figure 6.7**) is higher than the respective one of the other group (**Figure 6.8**); this fact implies that the lane reversal strategy (y_{ij} variables) is more extensively employed by the first set of solutions. Moreover, when setting side by side **Tables 6.7** and **6.8**, it can be observed that most (69%) of the φ^{rs} values of the first cluster (**Table 6.7**) are superior to those of the second group (**Table 6.8**); this fact points to the satisfaction of the generated demand being served better by the first set of results. In this respect, it can be concluded that the first set of solutions makes better use of both management strategies employed, thus, performing better in each of the individual OF indices considered (**Table 6.6**); it consistently achieves lower TNTT as well as distance-based and travel time-based OD-A values (the latter translated in ameliorated accessibility conditions) due to the more extensive use of the lane reversal strategy, while, at the same time, the improved performance of the model in those indices also leads to the satisfaction of higher demand rates (increased φ^{rs} values). The result is in agreement with and explanatory of the observation made in **Figures 6.5(a), 6.5(b)** and **6.5(c)**, that the best experiments of all CR / MR combinations belong to the first cluster.

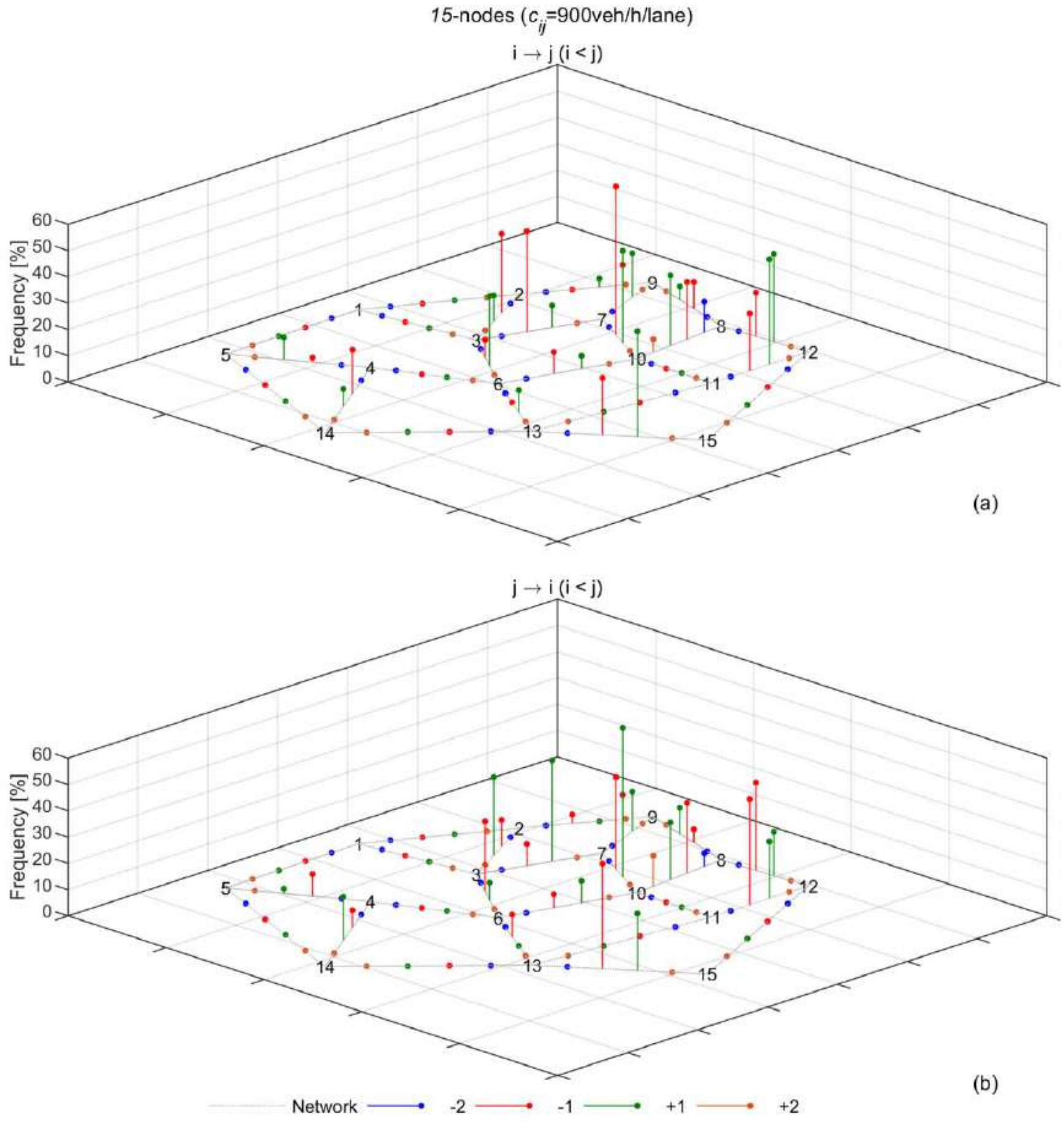


Figure 6.6 Relative lane-changing frequency of each of the network's links for the *15*-node network with c_{ij} = 900veh/h/lane

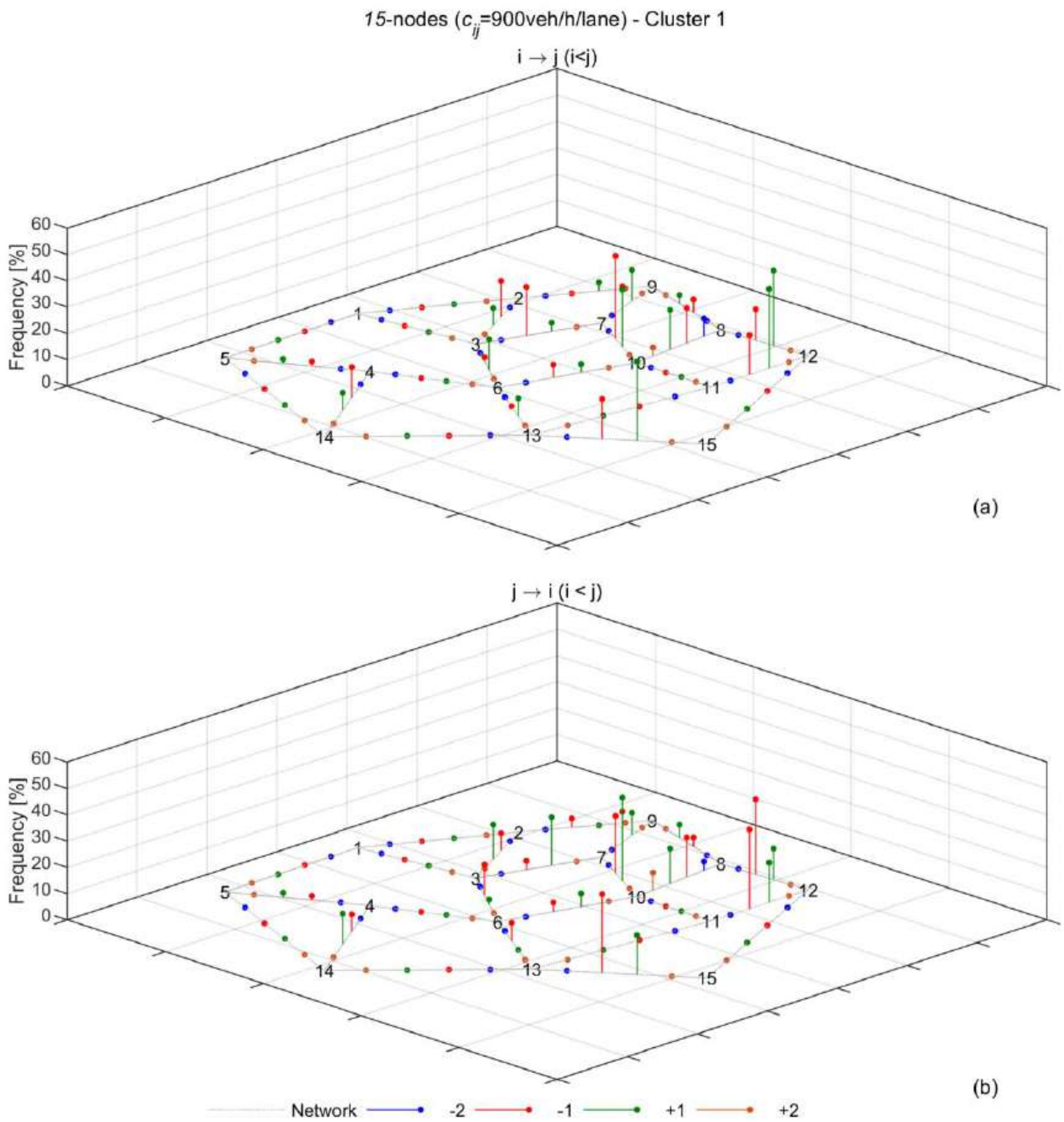


Figure 6.7 Relative lane-changing frequency of each of the network's links for the first (the left one) cluster of solutions of the *15*-node network with c_{ij} = 900veh/h/lane (reference to Figure 6.5(a))

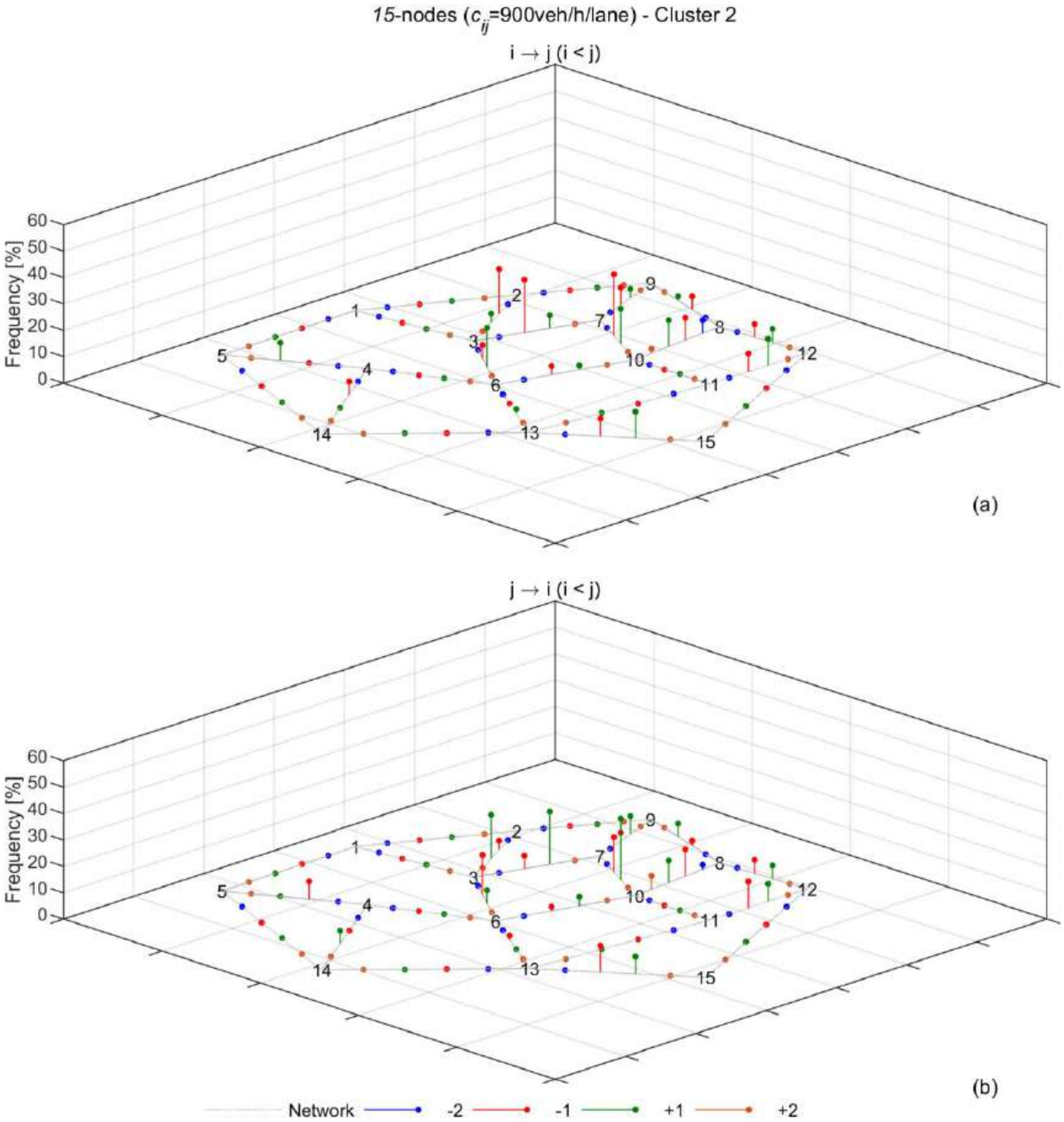


Figure 6.8 Relative lane-changing frequency of each of the network's links for the second (the right one) cluster of solutions of the *15*-node network with c_{ij} = 900veh/h/lane (reference to Figure 6.5(a))

Table 6.7 Demand adjustment rates between network's OD pairs for the first (the left one) cluster of solutions of the *15*-node network with c_{ij} = 900veh/h/lane (reference to Figure 6.5(a))

φ^{rs}	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0.826952	0.805050	0.754824	0.804476	0.736023	0.678144	0.713484	0.738445	0.576304	0.577383	0.765795	0.685856	0.745706	0.753529
2	0.851472	0	0.879849	0.742080	0.766854	0.822292	0.709317	0.762863	0.789245	0.689713	0.613033	0.772117	0.835475	0.762383	0.839641
3	0.830565	0.850898	0	0.682749	0.714009	0.740141	0.730657	0.643068	0.629777	0.622320	0.586336	0.714723	0.726137	0.626776	0.782627
4	0.837119	0.694443	0.657899	0	0.856261	0.830809	0.612263	0.726852	0.617908	0.700550	0.600514	0.744544	0.780237	0.849581	0.800450
5	0.804522	0.743436	0.716194	0.826829	0	0.847959	0.611922	0.763893	0.638557	0.705149	0.558054	0.745777	0.749410	0.848573	0.797374
6	0.734755	0.751517	0.786439	0.820561	0.749996	0	0.631943	0.813740	0.599099	0.828993	0.641721	0.762214	0.862779	0.751786	0.849927
7	0.596142	0.687406	0.659292	0.632653	0.579781	0.609112	0	0.762729	0.774153	0.719145	0.620651	0.726913	0.624193	0.607932	0.746238
8	0.673614	0.707017	0.629711	0.660398	0.689447	0.784761	0.698754	0	0.767211	0.815194	0.637369	0.822264	0.735382	0.603829	0.847730
9	0.674863	0.766171	0.667484	0.624234	0.635756	0.654487	0.763940	0.833700	0	0.669326	0.660133	0.865228	0.581665	0.569624	0.835720
10	0.597765	0.628812	0.627821	0.659396	0.680816	0.725457	0.698964	0.831545	0.685414	0	0.729035	0.762852	0.734646	0.621783	0.770503
11	0.598927	0.584495	0.621167	0.619531	0.602897	0.617567	0.611236	0.682915	0.591066	0.682395	0	0.841927	0.831258	0.867151	0.828474
12	0.708041	0.779384	0.654129	0.684409	0.672648	0.672243	0.653421	0.850080	0.804839	0.703217	0.893519	0	0.864538	0.804970	0.827066
13	0.681119	0.648698	0.652516	0.723843	0.701730	0.838236	0.604397	0.744762	0.611014	0.793891	0.864709	0.830065	0	0.858469	0.877744
14	0.799085	0.707010	0.615781	0.830092	0.872654	0.748450	0.602268	0.694205	0.609904	0.644399	0.832241	0.853601	0.814965	0	0.817171
15	0.683681	0.706656	0.720576	0.732158	0.694999	0.805322	0.667420	0.826494	0.793697	0.752107	0.889430	0.866415	0.829729	0.796071	0

Table 6.8 Demand adjustment rates between network's OD pairs for the second (the right one) cluster of solutions of the *15*-node network with c_{ij} = 900veh/h/lane (reference to Figure 6.5(a))

φ^{rs}	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0.858905	0.816809	0.794572	0.799925	0.657742	0.642475	0.578049	0.660805	0.580833	0.554486	0.603281	0.644143	0.822796	0.625279
2	0.855998	0	0.858173	0.654470	0.762509	0.755714	0.655217	0.661129	0.749587	0.613098	0.579546	0.610901	0.769991	0.774438	0.655986
3	0.873569	0.882229	0	0.625713	0.742274	0.739010	0.652068	0.609486	0.661605	0.615635	0.559814	0.573075	0.629732	0.615871	0.581926
4	0.819650	0.645896	0.622155	0	0.862672	0.777603	0.579451	0.648660	0.581016	0.686793	0.585131	0.583574	0.756962	0.841640	0.627725
5	0.852006	0.787858	0.710666	0.893314	0	0.792573	0.594010	0.627671	0.693596	0.654146	0.574327	0.614976	0.619394	0.879511	0.613355
6	0.771590	0.768877	0.794897	0.803883	0.774207	0	0.671465	0.832807	0.612369	0.830985	0.580180	0.596870	0.829358	0.769667	0.726001
7	0.651231	0.657078	0.671668	0.603274	0.592855	0.577103	0	0.732595	0.775450	0.743629	0.555359	0.592718	0.574543	0.609975	0.578630
8	0.592697	0.611761	0.652693	0.594405	0.615056	0.713318	0.652619	0	0.685429	0.861932	0.602996	0.821510	0.740386	0.622457	0.871256
9	0.681663	0.699662	0.626073	0.585812	0.655157	0.597189	0.735363	0.745021	0	0.663778	0.584158	0.693682	0.589359	0.604025	0.733957
10	0.600252	0.591666	0.645823	0.708476	0.637100	0.749342	0.667527	0.863232	0.649615	0	0.628365	0.594660	0.712023	0.619381	0.624563
11	0.596313	0.582185	0.570220	0.595841	0.595127	0.613576	0.603741	0.575279	0.592446	0.587364	0	0.859735	0.831338	0.867604	0.813471
12	0.627852	0.609425	0.567441	0.570993	0.574474	0.610382	0.565564	0.824343	0.656456	0.605093	0.867358	0	0.824180	0.816910	0.865639
13	0.630518	0.675108	0.727825	0.692179	0.643594	0.834855	0.595833	0.779105	0.612066	0.801387	0.831896	0.779668	0	0.890399	0.807982
14	0.828431	0.761924	0.607884	0.841746	0.856685	0.735033	0.576863	0.672556	0.579204	0.602087	0.843693	0.776910	0.857773	0	0.759376
15	0.596489	0.610041	0.597820	0.635210	0.603454	0.633793	0.572772	0.841400	0.689261	0.633394	0.848033	0.852005	0.793126	0.686883	0

6.3.2 Changes in the parameters θ and P

As already explained, modeling travel behavior is important in any circumstance for the estimation and assessment of network performance, and, thus, for the network design adopted (Li et al., 2009). This is even more so in the case of emergencies, where demand and supply variations can lead to changes in the travel behavior exhibited (Hsu & Peeta, 2013). Indeed, the deterministic routing principles are argued to be inadequate for modeling travel behavior (Prashker & Bekhor, 2004), with stochastic equilibrium models considered more appropriate for the representation of real-world problems (Xie & Liu, 2014; Prashker & Bekhor, 2004).

In this respect, a SUE model is adopted in the present case for the lower-level traffic assignment problem. From the literature, it can be observed that the SUE models do not systematically differentiate between the network's OD pairs and usually adopt a single value of the θ parameter over the entire network (Haghani et al., 2016). It is reminded that θ expresses the drivers' level of perception over the available routes to choose and the associated costs. As such, a low θ value introduces more stochasticity in the problem formulation, with consideration of higher dispersion rates among the drivers and the probability of choosing less attractive routes raising accordingly. In contrast, a high θ value implies the existence of more precise knowledge of the network's route structure and costs, thus, enabling the drivers to choose the best ones present. In the latter case, as θ reaches infinity, the SUE model collapses to its DUE counterpart (Prashker & Bekhor, 1999). Haghani et al. (2016) pointed out that the usual practice of using a single θ parameter over the entire network ignores the distance-dependent nature of OD pair stochasticity; that is, stochasticity levels increase with increasing path lengths and vice versa. The authors acknowledged, though, that the use of distinct θ values for each OD pair is impractical. In this context, and based on commuter questionnaire data, Haghani et al. (2016) estimated the value of θ lying within the [0.05, 1.11] interval. As such, the present study employs a uniform value of the dispersion parameter for all the analyses conducted; this is equal to 0.1 for the base case (medium variance) scenario. The value corresponds to the lower bound estimated by Haghani et al. (2016), with the selection made on the basis of circumventing any possibility that the SUE model collapses to the DUE one. However, further analyses, considering even lower θ values ($\theta = 0.01$, high variance scenario), are additionally performed. The scope is to investigate how sensitive the optimal solution may be to the incorporation of higher levels of travel behavior stochasticity in the problem formulation. Finally, two additional case studies, based on the deterministic assignment of traffic, are examined: the first one adopts the DUE principle, while the second one follows the system optimal (SO) model.

The transition from the stochastic to the deterministic assignment of traffic, induces changes in the formulation of the lower-level problem, which for the SUE case is described through eq. (4.15) - (4.24). More specifically, according to the DUE traffic assignment, users' route choices aim at the minimization of their own travel times, with the equilibrium reached when no user can further improve his travel time by unilaterally changing routes. Since the travelers are assumed to behave independently, the traffic flows achieved in this manner are stable and, in fact, constitute a true equilibrium (Sheffi, 1985). However, drawbacks of the DUE principle include the presumptions of travelers': (a) perfect knowledge over all arc costs, (b) consistency in making the right choices, and (c) homogeneity of behavior. In this respect, the DUE traffic assignment model, replacing eq. (4.15) - (4.24) of the original problem, is expressed as follows:

$$\min Z = \sum_{(i,j)\in A}\int_0^{x_{ij}} t_{ij}(w)dw \tag{6.1}$$

subject to:

$$\sum_{k\in K} f_k^{rs} = \varphi^{rs} q^{rs}, \forall (r,s)\in N_1 \tag{6.2}$$

$$f_k^{rs} \geq 0, \forall k\in K, (r,s)\in N_1 \tag{6.3}$$

$$x_{ij} = \sum_{(r,s)\in N_1}\sum_{k\in K} f_k^{rs}\delta_{ij,k}^{rs}, \forall (i,j)\in A \tag{6.4}$$

$$t_{ij} = t_{f,ij}\left(1+m_2\left(\frac{x_{ij}}{c_{ij}}\right)^{m_3}\right), \forall (i,j)\in A \tag{6.5}$$

with all sets, parameters and variables listed in **Table 4.1**.

As opposed to the DUE principle, where travelers are assumed to act selfishly during route selection, in the SO assignment, travelers act in favor of the whole system, picking routes that minimize the total system travel time instead of their own; this implies that, in the SO assignment, travelers may be able to decrease their own travel times by switching to other routes. In this respect, Sheffi (1985) highlights that this type of flow pattern is not stable and does not constitute a model of actual travel behavior and equilibrium. It should rather be viewed as a benchmark for the comparison of the respective travel time achieved through any other network design with the minimum value calculated through this type of assignment. The objective function of the SO model can be defined as:

$$\min Z = \sum_{(i,j)\in A} x_{ij} t_{ij} \tag{6.6}$$

subjected to the same constraints as in the DUE model (eq. (6.2) - (6.5)).

In addition to investigating the impact of the traffic assignment model on the optimal network solution, the effect of the penalty factor P, involved in the path generation process, is examined under two scenarios. P is initially assumed to be equal to 1 in both cases, that is, the impedances of the network links at first match their actual values. Next, while in the first scenario, the penalty step is set to 0.1 (i.e. 10% raise of link impedance), with the ultimate penalty value reaching the value of 2 (twofold increase), in the second case, the penalty step is set to 0.5 (50% increase), with the ultimate penalty value raising up to 5 (fivefold increase). The scope of the increased penalty step in the second case is to speed up the process of dissimilar path generation. In addition, the higher ultimate penalty value ensures greater diversity in the final path set, with a maximum number of ten loops executed in both cases.

First, the analyses regarding the θ parameter are presented. **Table 6.9** summarizes: (a) the average of all runs for the best CR / MR combination, and (b) the average of all runs for the *15*-node network with $c_{ij} = 900 veh/h/lane$ between: (a) the base case scenario $\theta = 0.1$, (b) the

$\theta = 0.01$ scenario, (c) DUE analysis, and (d) SO analysis. In addition, **Figure 6.9** provides an illustrative representation of: (a) the best, and (b) the average of all runs OF values for the aforementioned case studies. From the figure, it can be observed that both the best and the average values maintain the same hierarchical sequence between the experiments, with the SO analysis lying below all other case studies, followed by the results of the DUE experiments, the base case scenario and the $\theta = 0.01$ scenario. It can also be observed that the deterministic assignment of traffic (either following the DUE or the SO principle) provides the overall best results, with the performance of the network being equally improved under both hypotheses (normalized OF value). On the other hand, when stochasticity is additionally involved in the problem formulation, the respective experiments do not seem to be as effective in enhancing network performance as their deterministic counterparts. Indeed, the respective results appear to deteriorate as the value of the dispersion coefficient drops (i.e. the stochasticity level increases). It is notable that the best experiment of the base case ($\theta = 0.1$) scenario lies below the average values of the deterministic case studies, with its mean value, however, lying distinctively apart. This fact implies that the SUE ($\theta = 0.1$) case study can only reach the mean effectiveness of the DUE and SO cases when at its best. The results are even less favorable for the $\theta = 0.01$ scenario. However, the observed deterioration of network performance in the case of stochastic assignment is argued to be fictitious; it may not be viewed as model inferiority, but rather be attributed to the incorporation of a higher degree of realism that leads to modest results. The fact seems to confirm what has already started to be acknowledged in the literature (e.g. Xie & Liu, 2014; Prashker & Bekhor, 2004); that the widely applied deterministic assignment principles would preferably be used with caution (if at all) in a post-disaster network management context due to doubts regarding their suitability in such cases, as a result of systematical overestimations of the achieved network performance.

Moreover, as far as **Table 6.9** is concerned, it can be observed that, in terms of the $\theta = 0.01$ scenario, the deviation of the best CR / MR combination's average from the base case one is calculated as 45.55%, while the respective value for all runs is equal to 23.63%. The DUE and SO analyses exhibit even greater deviation values. The results are indicative of the differences that can occur in the problem's solution space as a result of the traffic assignment model followed and the specific parameters adopted.

As for parameter P, **Table 6.10** is analogous to **Table 6.9** with respect to the *15*-node network with $c_{ij} = 900 veh/h/lane$. The results consider: (a) the base case scenario of $P = 0.1$, and (b) the $P = 0.5$ scenario. In accordance, **Figure 6.10** is analogous to **Figure 6.9**. In this respect, **Table 6.10** shows that the deviation of the best CR / MR runs' average from the overall mean value is lower for the $P = 0.5$ scenario than it is for the base case one. In addition, the deviation of the best CR / MR combination's average of the $P = 0.5$ scenario from the base case one is calculated as 10.31%, with the respective value for all runs being equal to 3.37%. The results indicate that an increase in the penalty value assumed causes a raise in the discrepancy of the results. Looking at the results of **Table C.6** (Appendix C) and **Table 6.4**, it appears that the $P = 0.5$ scenario exhibits higher coefficients of variation in most of the OF terms (exception is the distance-based OD-A component, where the coefficients of variation are practically equal in both experiments). The percentage increase is greater in the travel time-based OD-A term, followed by the SD and TNTT terms. In comparison to the base case scenario, the absolutely best experiment of the $P = 0.5$ case performs better in the travel time-related components and, ultimately, the OF itself, with the average OF value of the best combination's runs, however, not exhibiting the same behavior. In addition, when the average OF value of all runs is considered, the base case scenario seems to achieve slightly improved results. The difference between the relative performance of the best and the average of all runs OF values between the case studies is illustratively depicted in **Figure 6.10**, where the respective scenarios' curves do not follow the same hierarchical sequence. In this respect, it can be concluded that the dissimilarity of paths pursued through the higher penalty value does not necessarily result in improved network performance. Although this appears to be the case when the best experiments of both case studies are concerned, on average, the increased penalty scenario has a similar and slightly worse performance than the base case one. It, therefore, seems that, in the $P = 0.5$ case, the improved values of the travel time-based components cannot compensate for the practically stable SD term and the slightly deteriorated distance-based OD-A term (that is, for the longer paths derived), thus, resulting in comparable results to the base case scenario (comparison of the average OF component values of the best CR / MR runs (**Tables C.6** and **6.4**)).

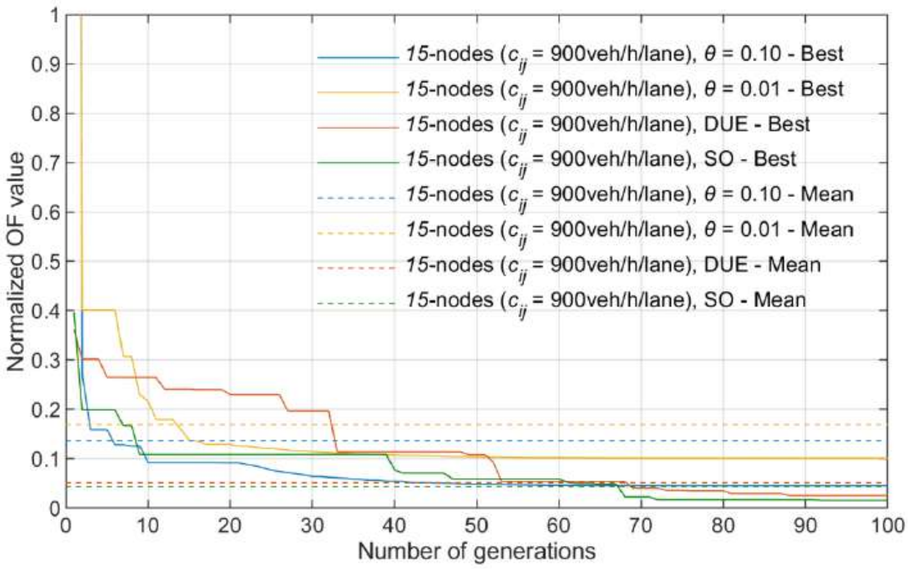


Figure 6.9 Best and average (of all runs) OF values for the *15*-node network with c_{ij} = 900veh/h/lane: (a) θ = 0.1 scenario, (b) θ = 0.01 scenario, (c) DUE analysis, and (d) SO analysis

Table 6.9 OF results for the *15*-node network with c_{ij} = 900veh/h/lane: (a) θ = 0.1 scenario, (b) θ = 0.01 scenario, (c) DUE analysis, and (d) SO analysis

	Objective function				Deviation from the base case scenario (%)		
	θ = 0.1	θ = 0.01	DUE	SO	θ = 0.01	DUE	SO
Average of all runs for the best CR / MR combination	0.123745	0.180112	0.045236	0.037550	45.550931	-63.444180	-69.655340
Average of all runs	0.137125	0.169533	0.051707	0.044010	23.633911	-62.292069	-67.905196
Deviation from the average of all runs (%)	-9.757521	6.240083	-12.514747	-14.678482	na	na	na

Table 6.10 OF results for the *15*-node network with c_{ij} = 900veh/h/lane: (a) P = 0.1 scenario, and (b) P = 0.5 scenario

	Objective function		Deviation from the base case scenario (%)
	P = 0.1	P = 0.5	P = 0.5
Average of all runs for the best CR / MR combination	0.123745	0.136503	10.309912
Average of all runs	0.137125	0.141750	3.372835
Deviation from the average of all runs (%)	-9.757521	-3.701587	na

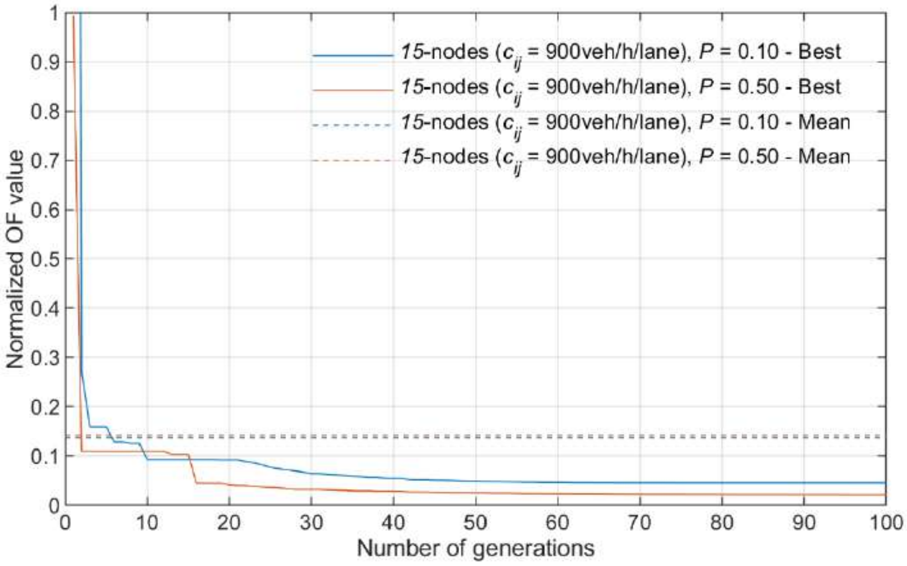


Figure 6.10 Best and average (of all runs) OF values for the *15*-node network with c_{ij} = 900veh/h/lane: (a) *P* = 0.1 scenario, (b) *P* = 0.5 scenario

6.3.3 Demand fluctuation

A demand augmentation scenario is examined, assuming a twofold increase of the demand. In this respect, each entry of the OD-pair demand matrix in **Table 6.2** is proportionally increased by 100% per case. The scenario takes place on the initial *15*-node network with $c_{ij} = 900 veh/h/lane$.

Table 6.11 summarizes (a) the average of all runs for the best CR / MR combination, and (b) the average of all runs for the *15*-node network with $c_{ij} = 900 veh/h/lane$ between: (a) the base case scenario $q^{rs'} = q^{rs}$, and (b) the $q^{rs'} = 2.0q^{rs}$ scenario. The results indicate that, in the second case study, the deviation of the best CR / MR runs' average from the overall mean value is very low (-0.26%), and in fact lower than the respective value of the base case scenario (-9.76%). A similar trend may also be observed in **Table 6.5**, when comparing the base case scenario to the ones of link capacity degradation (*15*-nodes, $c_{ij} = 500 veh/h/lane$) and complete component failure (*14*-nodes, $c_{ij} = 900 veh/h/lane$) (deviation values equal to 1.21% and 4.06% respectively). From **Tables 6.5** and **6.11**, it can be concluded that, as the operational characteristics of the network are led to extremes (increased demand rates, reduced supply attributes), the available solutions to the problem are accordingly restricted, thus, leading to reduced OF deviation values. In addition, the deviation of the best CR / MR combination's average of the $q^{rs'} = 2.0q^{rs}$ scenario from the base case one is estimated as 12.47%, with the respective value for all runs being equal to 1.76% (**Table 6.11**). The results confirm the intuitive perception that an increase in the generated demand can cause a deterioration of network performance.

Table 6.11 OF results for the *15*-node network with c_{ij} = 900veh/h/lane for: (a) the $q^{rs'} = q^{rs}$ scenario, and (b) the $q^{rs'} = 2.0q^{rs}$ scenario

	Objective function		**Deviation from the base case scenario (%)**
	$q^{rs'} = q^{rs}$	$q^{rs'} = 2.0q^{rs}$	$q^{rs'} = 2.0q^{rs}$
Average of all runs for the best CR / MR combination	0.123745	0.139181	12.474039
Average of all runs	0.137125	0.139545	1.764813
Deviation from the average of all runs (%)	-9.757521	-0.260848	na

Figure 6.11 provides an illustrative representation of: (a) the best, and (b) the average of all runs OF values for the two case studies examined. As illustrated in the figure, both the best and the average values maintain the same hierarchical sequence between the experiments, with the base case scenario performing better in both cases. It can also be observed that, despite the mean values of the scenarios being extremely close, the respective values of the best experiments lie distinctively apart. It can, therefore, be concluded that the increased level of demand assumed in the second case has a significant impact on the performance of the network, with the model not being able to reach the same maximum level of improvement (same normalized OF value) as the base case scenario does in its best run.

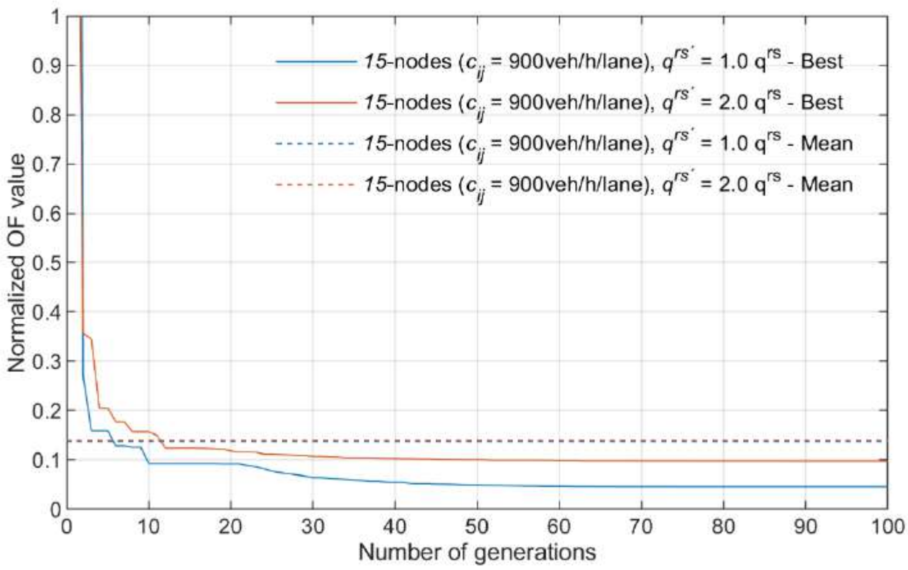


Figure 6.11 Best and average (of all runs) OF values for the *15*-node network with c_{ij} = 900veh/h/lane for: (a) the $q^{rs'} = q^{rs}$ scenario, and (b) the $q^{rs'} = 2.0q^{rs}$ scenario

6.3.4 Sensitivity analysis

A sensitivity analysis is conducted to examine the influence of the three upper-level OF terms' weighting coefficients on the final OF values achieved. To eliminate the effect that any other parameters might had on the final outcome, the base case scenario (*15*-node network, $c_{ij} = 900veh/h/lane$) is used in the present case, with the best experiment setting the basis for the analyses performed. As indicated in **Table 6.4**, the optimal solution corresponds to the CR:

0.80 / MR: 0.05 combination, with its TNTT, SD, OD-A and OF values acting as benchmark for the sensitivity analysis results. Six combinations of the weighting factors are investigated. These involve the successive increase (or decrease) by an arbitrarily defined rate of 50% of each one of the weighting coefficients, with the other two factors remaining, in each case, equal to their initial values of 1/3. In this respect, the six combinations investigated are the following: (a) $w_1^{'} = 1.50 w_1, w_2^{'} = w_2, w_3^{'} = w_3$, (b) $w_1^{'} = 0.50 w_1, w_2^{'} = w_2, w_3^{'} = w_3$, (c) $w_1^{'} = w_1, w_2^{'} = 1.50 w_2, w_3^{'} = w_3$, (d) $w_1^{'} = w_1, w_2^{'} = 0.5 w_2, w_3^{'} = w_3$, (e) $w_1^{'} = w_1, w_2^{'} = w_2, w_3^{'} = 1.50 w_3$, and (f) $w_1^{'} = w_1, w_2^{'} = w_2, w_3^{'} = 0.50 w_3$.

Table 6.12 summarizes the analysis results, with the polar diagrams of **Figures 6.12(a), 6.12(b)** and **6.12(c)** providing illustrative comparisons of the combinations' best runs examined in pairs of modified weighting coefficient (that is, (a) with (b) for w_1 (**Figure 6.12(a)**), (c) with (d) for w_2 (**Figure 6.12(b)**), and (e) with (f) for w_3 (**Figure 6.12(c)**)), each time along with the base case scenario (blue line). In the figures, the (w_1, w_2, w_3) combinations are indicated by lines of different colors (green and red), with the four diagram axes corresponding (in a clockwise manner) to the OF, TNTT, SD and OD-A components respectively.

It can be seen that, when modifications of the w_1 parameter are considered (**Figure 6.12(a)**), the changes in the form of the diagram are modest. The SD term remains practically stable across the analyses, while the drop in the TNTT term in combination (b) cannot compensate for the increase in the respective distance-based OD-A term due to its small value. As such, the increase in the OF value of both combinations (a) and (b) can be attributed to the increase of the OD-A term, with augmented values of the distance-based component. In this respect, the base case scenario provides the lowest OF value between the combinations, with the second best belonging to combination (b), which favors the TNTT term.

On the other hand, when modifications of the w_2 parameter are considered (**Figure 6.12(b)**), the diagram appears to change shape so that the values of the base case scenario remain between those of the other two combinations. From **Figure 6.12(b)** and **Table 6.12** it can be observed that the variations of the SD term cause substantial change to the OD-A component and subsequently to the OF value. In particular, an increase of the SD term causes significant deterioration of the distance-based OD-A component, albeit a drop in the OF value. The results are reasonable, since a greater fraction of the demand allowed to travel on the network's links is expected to induce lower accessibility values. The opposite is valid for an SD decrease, with the travel time-based indices ameliorated in this case. As such, combination (c) appears to have the best performance between the three in OF terms.

Finally, when modifications of the w_3 parameter are considered (**Figure 6.12(c)**), the diagram moves considerably along the OD-A and OF axes, with the other two terms appearing as practically stable. The discrepancy in the OD-A and OF terms observed in this case is significant, with the OF term of combination (f) taking negative values and reaching the lowest point of all the sensitivity analysis combinations examined. The negative sign in this case is purely arithmetical, since the respective OD-A component cannot override the SD one, and has no physical meaning or complications. In this respect, combination (f) arises as the best, not only between combination (e) and the base case one, but among all the analyses conducted.

The sensitivity analysis results highlight the importance of the SD term and the distance-based OD-A component in the final OF value. The significance of those indices, as opposed to the travel time-based ones, may be attributed to their higher absolute values when involved in a common mathematical expression with the other two terms. From **Table 6.12**, it can be observed that the model proves to be very effective in reducing the travel time-based indices; this is achieved through the extensive use of the lane reversal strategy. The other terms, however, do not exhibit the same flexibility, since the length of the paths involved in the distance-based OD-A component cannot drop under a certain value, while the satisfied demand rates cannot increase over the initially generated demand. As such, the sensitivity analysis results seem to be guided by the balance between these two inelastic (but high value) terms, while the travel time components (TNTT and travel time-based OD-A), despite being variable, have values that are too low to affect the final outcome.

Table 6.12 Sensitivity analysis results for the *15*-node network with c_{ij} = 900veh/h/lane

	$w_1'=a*w_1$	$w_2'=b*w_2$	$w_3'=c*w_3$	Objective function best runs					Objective function (average of all runs)
				Total network travel time	Satisfied demand	OD-pair accessibility		Objective function	
	a	b	c			Distance-based	Travel time-based		
Sensitivity analysis	**1.00**	**1.00**	**1.00**	**0.018254**	**0.248638**	**0.247505**	**0.028390**	**0.045511**	**0.123745**
	1.50	1.00	1.00	0.018885	0.237643	0.300257	0.025389	0.106888	0.147038
	0.50	1.00	1.00	0.007991	0.246948	0.303081	0.028026	0.092150	0.134305
	1.00	1.50	1.00	0.016203	0.372425	0.333402	0.028097	0.005277	0.037928
	1.00	0.50	1.00	0.005994	0.121984	0.247062	0.009848	0.140920	0.245377
	1.00	1.00	1.50	0.013640	0.235113	0.454661	0.038874	0.272062	0.313151
	1.00	1.00	0.50	0.016817	0.250549	0.140696	0.015767	-0.077269	-0.042556

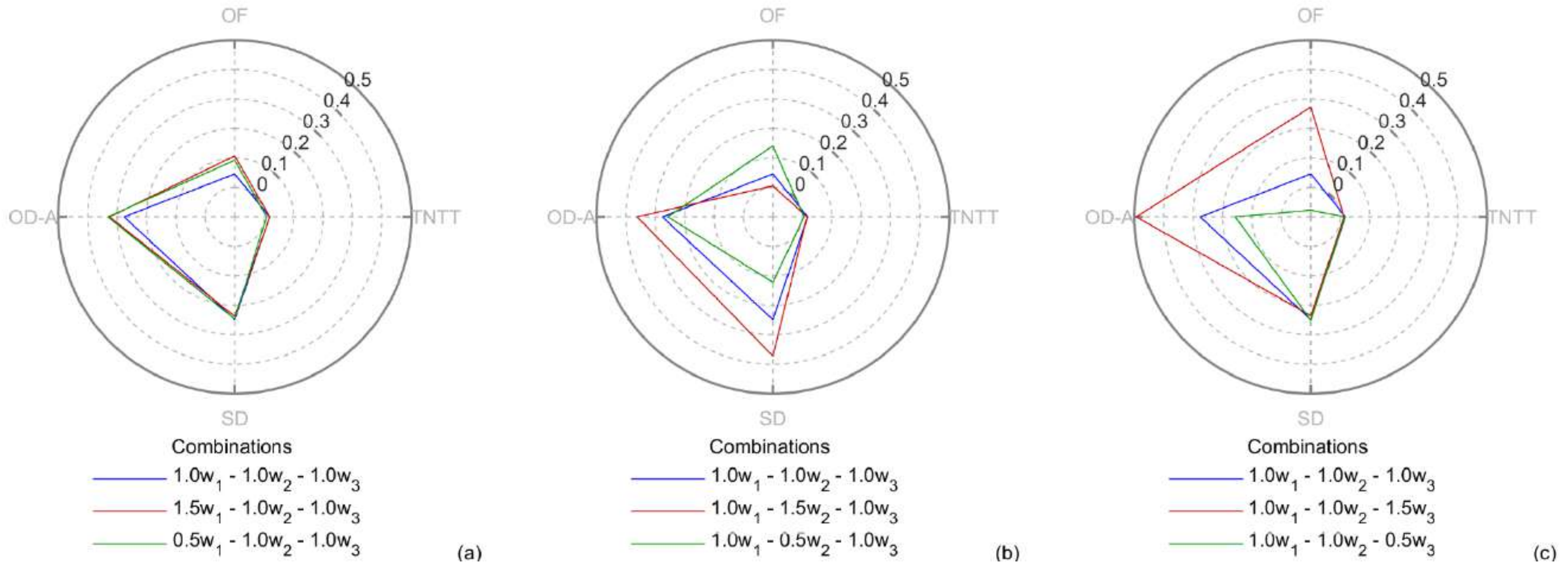


Figure 6.12 Sensitivity analysis results for the *15*-node network with c_{ij} = 900veh/h/lane (best OF runs)

7. Conclusions

7.1 Overview, research findings and contribution

Although not at the forefront of emergency management rationale, in cases of catastrophes, transportation networks prove their role as vital lifelines, ensuring network connectivity and providing the necessary ways for the execution of a series of emergency operations. At the same time, transportation networks are themselves vulnerable to structural and functional degradation, which, combined with the stochasticity involved in the travelers' behavior and the diverse needs arising under emergency conditions, mount the pressure for the need of effective network management; this will, most probably than not, require a re-structuring of network functioning, often in the form of network re-configuration, along with the employment of other operational strategies. In this context, the development of appropriate management tools that can account for the network's operational state and the individuals' behavioral aspects and optimally re-structure them to the benefit of overall network functionality are of significant practical importance. In such settings, these tools can help facilitate the related emergency operations and provide critical added value to the whole disaster management process.

In this context, the present thesis endeavors to advance the state-of-the-art in disaster management by providing a framework that supports and promotes the enhancement of network functionality in an integrated manner. The thesis distances itself from the consideration of specific network operations and examines network functioning from a wider perspective, that of generalized network management. In order to do so, the framework explicitly considers the operational state of the network and users' behavioral patterns and attempts a system re-organization on the basis of defined objectives. This is achieved through the use of two distinct management strategies (lane reversal and demand regulation), the development of a multi-aspect measure of performance (including travel time, satisfied demand and OD-pair accessibility indices), the formulation of suitable hypotheses regarding route construction (iterative path generation following the link penalty approach) and route choice (traffic assignment according to the SUE principle following the PCL model) and the selection of an appropriate analysis concept (vulnerability analysis). All the above are combined under a common framework in order to provide a re-configured network with re-allocated demand so that network performance is maximized. Appropriate solution methodologies (a GA coupled with a traffic assignment process) are employed to handle the associated computational burden since the model is formulated as a variant of the mixed network design problem (MNDP). The efficiency and efficacy of the model in enhancing network performance is demonstrated in a set of case studies, where the implicit relationship between the problem's optimal solution and changes in its input parameters is explored; the scenarios considered extend from changes in the network's physical attributes and modifications of problem parameters to fluctuations of the demand and sensitivity analysis.

The dissertation ultimately provides a novel, structured and sound conceptual and mathematical framework for efficiently handling the various needs arising in the period following a catastrophe. The framework can be used as a planning tool by transportation professionals and stakeholders and adds a higher degree of realism in the decision-making process by explicitly accounting for some of the stochasticities that are either way present in transportation management, but possibly exacerbated in a post-disaster setting. As such, the dissertation attempts to fill in the associated gap by advancing current research efforts which have generally disregarded randomness from their NDP formulations.

In this respect, the main research findings from the analyses conducted and the contribution of the dissertation to the literature can be summarized as follows:

- Regardless of the actual case study examined, the model's solution space has a more or less fixed form (see **Figure 6.5**), with the best results generally accumulating in two sets of solutions. Further analysis of this form points to the fact that these sets correspond to results of distinct quality, with the first group systematically performing better in each of the individual objective function (OF) indices considered; this is realized by lower total network travel time (TNTT) as well as distance-based and travel time-based origin - destination pair accessibility (OD-A) values (the latter translated in ameliorated accessibility conditions) and higher satisfied demand (SD) rates. As such, it seems natural that the best experiments of all crossover rate (CR) / mutation rate (MR) combinations belong to this group. The discrepancy of performance between the two sets may be attributed to the better use of both management strategies by the first one; this is indicated by the higher lane-changing frequency of the network's links (that is, regular changes in the links' number of lanes imply more extensive use of the lane reversal strategy) and the increased rates of satisfied demand achieved by the first set.

- In general, the proposed model is more sensitive (higher coefficients of variation) to the problem's travel time aspect (total network travel time (TNTT) and travel time-based origin - destination pair accessibility (OD-A) terms) than to the demand parameter (satisfied demand (SD) term) or to the length of the paths constructed (distance-based OD-A term); the latter two terms remain relatively stable throughout the analyses conducted per case.

- The results of the sensitivity analysis highlight the importance of the satisfied demand (SD) and distance-based origin - destination pair accessibility (OD-A) components in the final objective function value. When variations of the weighting coefficients are involved in the analysis, the higher absolute values of the SD and distance-based OD-A terms seem to be the decisive factor in the final outcome, since the travel time ones have values that are too low to compensate for the increase and / or decrease of the other two components and to ultimately affect the final objective function value.

- In most of the case studies investigated, the algorithm reaches convergence quite quickly (approximately between the 20th and the 30th generation), thus, implying that a reasonably good solution to the problem could be found in about 55 - 85 min (Intel (R) Core (TM) i7 processor - 6700 CPU (3.40GHz) with 16GB of RAM). Therefore, the termination criteria related to the number of generations performed and to the running time elapsed could be accordingly relaxed.
- It is not possible to locate a common optimal crossover rate (CR) / mutation rate (MR) combination for all the scenarios examined, as in most case studies the absolutely best experiments correspond to different combinations. Nevertheless, the CR: 0.90 and the MR: 0.05 values perform a little bit better than the rest ones investigated; this, however, does not necessarily occur when in combination with one another.
- As expected, demand and supply changes in the period following a catastrophe are found to have a clear effect on the achieved network performance. In particular, both complete (removal of links and / or nodes) and partial (limitations on link capacity) component failures can cause substantial reduction in network functionality, with the same also being valid for possibly increased demand rates. The proposed model, despite not being able to compensate for the initial deterioration of the network's operative features in order for them to reach the base case scenario, is particularly effective in enhancing network performance across all the case studies examined.
- The analyses also suggest that changes in the network's operational attributes (decline in the supply characteristics and / or an increase in the demand) have generally a limitation effect on the available solution space, thus, leading to results that lie closer to one another (exhibiting reduced deviation).
- The traffic assignment process is indeed found to have a significant impact on the analysis outcome. In particular, the incorporation of stochasticity in the route choice process tends to lead to inferior analysis results in comparison to the ones derived from the deterministic assignment of traffic. As such, the stochastic models do not seem, at first, to be as effective in enhancing network performance, as their deterministic counterparts. However, the enhancement of network performance provided under the DUE and SO principles is argued to only be theoretical; these models are known to not be appropriate to capture the travelers' route choice mechanisms under emergency conditions. In this respect, the analysis results obtained from the stochastic assignment of traffic are in alignment with the incorporation of a higher degree of realism, as opposed to the overestimation of network performance that is systematically realized when deterministic routing principles are used.
- In terms of the path generation method, the results indicate that consideration of a higher degree of path dissimilarity does not necessarily result in improved network performance. Indeed, although ameliorated objective function (and / or individual term) values may circumstantially occur, specific outcomes can neither be generalized, nor can they support the higher penalty option. The fact may be attributed to the increased discrepancy

of the results observed in such cases, which leads to mediocre overall performance and, thus, to skepticism regarding the added value expected from the analysis.

- Throughout the analyses, the proposed algorithm has generally proved to perform steadily and produce consistent results; the conclusion is reached by the calculated coefficients of variation regarding the average objective function values per scenario examined. It is argued that the resulting coefficients of variation would not be possible (nor should it be expected) to be exceptionally low, since the algorithm each time runs on a different network realization (due to the lane reversal strategy employed) and additionally adopts distinct demand regulation rates. This fact explains the difficulty of the proposed algorithm to reach a unique, ultimate solution and, therefore, achieve even lower discrepancy values in the objective function results.

7.2 Limitations

Implementation of either management strategies (lane reversal and / or demand regulation) remains a topic of interest since the difficulties arising in this respect, and their implications thereof, may be substantial. More specifically, lane reversal, despite being remarkably effective in reducing network travel times, it inherently implies a change in network configuration. This change, however, due to its short-term and emergent character, defies any pre-existing conception of the travelers' perfect knowledge over the network structure and the associated costs, thus, indicating the inadequacy of and the need to move away from the extensively used DUE principle. In addition, in order to ensure its consistent implementation, lane reversal necessitates a considerable amount of resources (human and / or economic) and time to be employed on the network, on top of the need for a clear and strong organizational structure that enables, establishes and promotes communication, coordination and cooperation between the parties involved. In this respect, lane reversal seems to be more easily applied on roads whose functional characteristics are such, that the expected benefits from the implementation of the strategy will override the associated costs (e.g. arterials with multiple lanes per direction and increased speed limits). Moreover, due to the difficulties present, lane reversal may generally not be a spontaneous decision on behalf of the authorities, with strategic implementation plans on the basis of different scenarios better be prepared beforehand.

On the other hand, regulation of the demand may prove to be even more challenging. The possibility of intervening in the first step of transport modeling sounds, at first, promising, with its actual way of implementation being, however, hard to specify. It seems that regulation of the demand would necessitate a means of communication to the prospective network users as well as good compliance rates on their behalf. On the contrary, it would also premise a way of enforcement, if voluntary conformance is not achieved. Whereas communication of orders to the public could be done in various ways in the case of complete travel prohibition, things become more complex in the case of partial travel restriction (as in the problem at hand), where potential network users must first be made aware of whether they are allowed to travel. As such, and in order to serve the scope of the strategy, communication in the second case must take a more individualized form, which present and future technology is expected to allow. In addition, conformance of the public to orders is a topic of debate, since research on the underlying behavioral mechanisms that shape the individuals' reactions under emergency situations are mostly qualitative and the results of their comparative evaluation are presently inconclusive. As such, users' compliance should not be taken for granted, with appropriate enforcement mechanisms possibly having to be set in place. In this respect, it comes as no surprise that the difficulties related to the actual implementation of the demand regulation strategy have made it, for the time being, a rather theoretical concept than a practically applicable one.

In terms of the route (path) generation algorithm, it must be noted that the formulation of (sufficiently) dissimilar routes is clearly dependent upon the available alternatives at each time; these are realized through the upper-level problem designation with respect to the reversal of roadway lanes and the resulting network configuration. In this respect, the network structure may pose greater difficulties in the case of contraflow operations, where bi-directional links may become, after lane re-allocation, one-way streets. In addition, the existing cost (impedance) relationship between concurrent links can have a decisive influence on the creation of dissimilar paths. Indeed, in the case of two links originating from the same node, a notable difference between their costs could lead the penalty value to go to extremes in order for a different route to occur. However, the use of such high penalties can cause the formulation of cost prohibitive routes that would generally not be favored by the network users. Therefore, the criticality of the penalty term implies that its selection should bridge two distinct objectives: promote the diversity of the generated path set while ensuring that the routes created are reasonable from a user perspective. Last, the iterative construction of the paths raises the computational complexity of the model. In particular, since each of the individuals comprising the population constitutes a possible solution with a respective, accompanying network configuration, the path generation algorithm runs for each one of those networks in search of the associated shortest paths. Path construction, in this way, may prove to be challenging, especially in cases where the penalty value needs to be set high, the penalty step remains relatively small and the algorithm has to repeat itself many times.

Finally, as far as the SUE traffic assignment problem is concerned, selection of an appropriate value for the dispersion coefficient θ, that can adequately describe the behavioral characteristics of the travelers as well as the topological and operational attributes of the network, is especially challenging. In this context, availability of real data is deemed necessary for the estimation of θ, irrespectively of the actual implementation method followed. Two distinct cases may be recognized in this respect: (a) the use of a single value of θ over the entire network (considering uniform and OD-independent behavior of the travelers), or (b) the use of a structured formulation of the dispersion coefficient (accounting for the distance-dependent nature of OD pair stochasticity) (Haghani et al., 2016). Despite the first case being used more often, the latter case is able to raise the modeling accuracy in real-sized networks at the expense of increased computational burden. Therefore, with respect to each network's inherent characteristics, selection of the θ value should be representative of the desired level of stochasticity incorporated in the model.

7.3 Future research paths

Although network management extends from the period preceding to the period succeeding a catastrophe and involves a range of activities aiming at the preservation of the structural integrity of the infrastructure and the enhancement of system performance, most of the literature has until now focused on the study of evacuation operations. This may be attributed to the significance of evacuation in terms of safeguarding human life and health; in this respect, the role of evacuation is undeniable. Nevertheless, the need for generalized network management in the aftermath of a disruptive event is equally essential and practically more frequent; this premises the consideration of bi-directional traffic movements to accommodate the diverse needs arising, the employment of appropriate management strategies and the combination of different types of performance measures to fit the objectives set, as well as the consideration of users' route choice behavior to more realistically capture the traffic patterns observed in practice. In this context, the literature is still short of studies attempting a holistic approach to network management, even more so when both the pre- and the post-disaster phases are to be considered. Indeed, discretizing the disaster management framework may facilitate the study of individual operations, but lacks realism on both the theoretical and the operational / tactical level. In practice, this will, most probably than not, reveal planning inconsistencies during implementation, when the separate frameworks are to be united. It is, thus, argued that investigation of a specific type of operation is indeed helpful in gaining insight, but does not, in any case, suffice in terms of preparing and planning for real-world problems which premise the consideration of various problem aspects as well as the continuity of hypotheses and actions.

Yet, another area in need of further investigation refers to the behavioral parameters involved with the individual and mass responses exhibited during situations of crises and especially during evacuations. Research shows that the decision to evacuate is largely dependent upon the perception of an impending threat as being real and the assessment of its possible consequences, with the available time to react, the existence of an emergency plan and the location of family members evaluated as equally important parameters (Helsloot & Ruitenberg, 2004). Apart from the decision to evacuate, though, these characteristics also interfere with the route choices made, thus, affecting the totality of the evacuation process. In addition, in areas prone to disasters, communities may develop what is known as "disaster sub-cultures", interpreted as the cultural adaptation to those recurrent threats (Granot, 1996). "Disaster sub-cultures" are hazard-specific and premise the re-organization of societal roles to fit the ones reserved for these situations (Granot, 1996). Community re-organization, however, does not necessarily imply a better reaction to disaster phenomena since this may be compromised by a false sense of security or the repetition of past mistakes (Granot, 1996). In this respect, an adverse manifestation of an area's "disaster sub-culture" may be the "cry wolf" syndrome, referring to an individual's refusal to comply with official orders and recommendations due to repeated former conformance to what later appeared to be a false alarm (Sorensen & Sorensen, 2007). Compliance with orders, however, does not only depend on one's own will to follow them, but also on the actual ability to do so. People in need of assistance (e.g. the elderly and the children, people with disabilities, health or mental issues, people with limited economic resources, tourists, prisoners etc.) tend to exhibit lower evacuation rates than the rest of the population (Turner et al., 2010). This may lead to discrepancies between the evacuation plans devised and the observations made in practice; while the authorities may plan for the maximum demand possible, the actual number of evacuees may be much lower (Turner et al., 2010), possibly implying a waste of resources in addition to the insufficiency of the plan to fulfill its scope, namely the transport of all the threatened population to safety. On the contrary, a lot of studies in the field (e.g. Bish & Sherali, 2013; Afshar & Haghani, 2008; Sbayti & Mahmassani, 2006) suggest just the opposite; that the demand may exceed roadway capacity and overwhelm the infrastructure.

It is, thus, clear that the, until now, inability to incorporate evacuees' behavioral characteristics into the distinct steps of planning (demand estimation, destination selection, route choice) introduces vagueness into the network management effort. This may be attributed to the whole decision process being highly individualized as well as to the lack of available data or the difficulties arising in their exploitation. More specifically, surveys (either of revealed or stated preferences) have always been the major source of evacuation behavioral data. Despite their reliability, though, revealed preference data should preferably not be used as behavioral predictors in circumstances other than the ones they relate to (Gudishala & Wilmot, 2010), while stated preference data may prove to be in weak correspondence to the actual emergent behaviors and should better be treated as behavioral expectations rather than intensions (Kang et al., 2007). Consequently, evacuation's behavioral aspects have mostly been studied from a qualitative perspective (Hsu & Peeta, 2013; Chiu & Mirchandani, 2008). Research emphasis should, thus, be placed on the, to the degree possible, generalization of the behavioral patters observed in practice and to the methodologically sound quantification and incorporation of them into network management modeling.

Furthermore, in disaster situations, the role of information has been recognized as significantly important (Quarantelli, 2007). It has been proved that compliance rates generally rise when people assess the information received as precise and complete (Perry & Lindell, 2003), with inaccuracy and inadequacy of information leading to complacency or adverse actions (Jaeger et al., 2007). In this respect, the use of various information sources such as those used or proposed by the intelligent transportation system (ITS) platforms (referring to the application of information and communication technologies (ICT) in transportation systems), mass media and social media could assist in disaster management by providing updates, guidance and recommendations to the public as well as feedback to the stakeholders. Apart from evacuation, though, information provision may prove to be valuable to other types of operations as well; in 2008, a survey of 24 State government directors of emergency management in the US revealed that, despite its overall good performance, information technology (IT) appears to be more effective during the response phase (Reddick, 2011). With literature on the application and influence of ITS on disaster operations essentially missing, mass media coverage has been acknowledged to have a significant impact on the perception of disaster phenomena and the response to them (Houston et al., 2014). The same authors are also supportive of the use of social media during catastrophes due to their ability to provide timely, two-way communication. However, as with all sources of information, attention should be paid not only to the availability of information, but also to its type and quality. Information should generally be comprehensive (Leidner et al., 2009), with doubts about the accuracy and credibility of the information derived from the social media and crowd-sourcing playing a major role in the reluctance of the stakeholders to use it (McCormick, 2016). Information accuracy may be compromised by intention, exaggeration or even accidentally; this can be alleviated by using trusted sources or by verifying the information received through the network (Heinzelman & Waters, 2010).

In any case, information provided in a top-down approach (from the authorities to the public) is useful in conveying the desired messages, whereas two-way communication (from the authorities to the public and vice versa) holds the potential of raising the efficiency of disaster management. This, however, may only be valid when obstacles regarding information accumulation, processing, transmission and reception are overcome, at least to some extent. As such, the formulation and employment of appropriate tools in this direction can benefit all process steps, extending from the collection and classification of various data types, to the detection and dismissal of false or unnecessary information and the conversion of the rest into precise and easily comprehensible forms on the basis of the targeted audience. As already explained, information scanning is especially important when social media or information crowd-sourcing is involved, while as far as the mass media are concerned, sensationalizing or misreporting should be diminished. Ensuring information credibility is a prerequisite for the adoption of IT in disaster management with the availability of the required resources for the acquisition of the respective infrastructure and devices (especially in the case of ITS) coming next. However, research in the early detection of false information and prevention of its dispersion is scarce (Halse et al., 2018), while studies evaluating the impact of ITS, social media, mass media and crowd-sourcing on the actual network performance are also currently absent.

Finally, it can be observed that during network performance assessment, the focus gradually shifts to the underlying basis, that is the provision of more accurate representations of post-disaster network conditions; partial failures and multi-component disruption scenarios are more frequently encountered in the recent literature. However, research currently lacks any sophisticated models that could account for the dependencies present in real-world systems, with the term here not exclusively constrained to the interactions between system components, but also extending to the ones existing between the systems themselves (inter-dependencies). Indeed, the independence assumption between the systems' and components' failure states is expected to eventually give its place to the consideration of the complex relations between them, leading to an in-depth understanding of system dynamics and, thus, to the extraction of more precise system realizations and improved performance estimations. However, with respect to disaster management, consideration of component and system dependencies is still at its infancy since the incorporation of such assumptions into modeling is, until now, very limited.

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Appendix A

A.1 GEV-based models

A.1.1 The path size logit (PSL) model

The PSL model, initially proposed by Ben-Akiva & Bierlaire (1999), is another modification of the MNL to account for path overlapping. According to it, path overlapping prevents users from considering the respective paths as distinct alternatives. Path size therefore may no longer be considered constant and equal to one but it may need re-adjustment. Correction comes in the form of path size log addition to path utility when estimating the route choice probabilities. Path size has a maximum value of one; that is in the case of discrete paths, where there is no need for utility re-adjustment. In the general case though, path sizes will be less than one, depending on a path's link lengths as well as on the relative length of the paths sharing a link. On that basis, the probability of choosing route k can be defined as:

$$P_k = \frac{\exp\left(V_k + \ln S_k\right)}{\sum_{l \in K^{rs}} \exp\left(V_l + \ln S_l\right)} \tag{B.1}$$

where S_k is the size of path k. Various formulations have been proposed in the literature for the estimation of path size. Ben-Akiva & Bierlaire (1999) developed the following form:

$$S_k = \sum_{i \in \Gamma_k} \frac{l_i}{L_k} \frac{1}{\sum_{j \in K^{rs}} \delta_{ij} \frac{L_{K^{rs}}}{L_j}} \tag{B.2}$$

where L_k is the length of route k, l_i is the length of link i, Γ_k is the set of links comprising route k, δ_{ij} is one if path j includes link i and zero otherwise, K^{rs} is the set of routes for OD pair $\left(r, s\right)$, and $L_{K^{rs}}$ is the length of the shortest path in K^{rs}. Ramming (2002) on the other hand, proposed a slightly modified expression of the above equation by weighing the contributions of the paths on the basis of their lengths' ratio.

$$S_k = \sum_{i \in \Gamma_k} \frac{l_i}{L_k} \frac{1}{\sum_{j \in K^{rs}} \left(\frac{L_k}{L_j}\right)^{\gamma} \delta_{ij}} \tag{B.3}$$

where γ is a parameter to be estimated.

The difference between the PSL and the C-logit model lies in the role that each correction term assumes in the formulation. In the C-logit model, the commonality factor is always greater than or equal to one, indicting the need to reduce a path's utility due to its similarity with other paths. On the contrary, in the PSL model, path size is always less than or equal to one, indicating the fraction of the path that constitutes a "full" alternative (Prashker & Bekhor, 2004; Prato, 2009).

A.1.2 The implicit availability / perception (IAP) logit model

The IAP model is a modification of the MNL, developed by Cascetta & Papola (2001). Scope of the model is to account for path unavailability or unawareness in the route choice process. The probability for traveler n of choosing path i can be estimated by:

$$P_n(i) = \frac{e^{V_i + \ln \mu_n(i)}}{\sum_{j \in M} e^{V_j + \ln \mu_n(j)}} = \frac{\mu_n(i) e^{V_i}}{\sum_{j \in M} \mu_n(j) e^{V_j}} \tag{B.4}$$

with M being the master choice set, and $\mu_n(i)$ indicating path availability or awareness ($\mu_n(i)$ equals one, if path i is available and zero otherwise). When path availability is not known beforehand, it can be treated as a random variable with expectation $\overline{\mu_n}(i)$. This value replaces $\mu_n(i)$ in the equation above. However, it has been proven that a second-order Taylor series expansion with the maximal variance of $\mu_n(i)$ resulting from a Bernoulli distribution can yield better results:

$$P_n(i) = \frac{\exp\left[V_i + \ln \overline{\mu_n}(i) - \dfrac{1 - \overline{\mu_n}(i)}{2\overline{\mu_n}(i)} \right]}{\sum_{j \in M} \exp\left[V_j + \ln \overline{\mu_n}(j) - \dfrac{1 - \overline{\mu_n}(j)}{2\overline{\mu_n}(j)} \right]} \tag{B.5}$$

Cascetta & Papola (2001) assumed a binary logit specification for $\overline{\mu_n}(i)$:

$$\overline{\mu_n}(i) = \frac{1}{1 + \exp\left(\sum_{k=1}^{K} \gamma_k Y_{ink} \right)} \tag{B.6}$$

where Y_{ink} is the k^{th} variable related to the availability / awareness of alternative i for traveler n and γ_k is a parameter to be estimated.

A.2 The Multinomial Probit (MNP) model

The MNP model, first proposed by Daganzo & Sheffi (1977), is an alternative to the MNL model which explicitly captures the correlation among all alternatives (Ben-Akiva & Bierlaire, 1999). By definition, the model assumes that the error term of the utility function is normally distributed and that the joint density function of the error terms follows the multivariate normal distribution. The model is characterized by a K-length vector of means and a $K \times K$ covariance matrix, with K being the number of routes for a specific OD pair. Despite conserving its shape under linear transformation, the model lacks the ability of expressing its cumulative normal distribution in a closed form.

In a binary choice model, the probability of choosing one route over another can be expressed as:

$$P_1 = P\left(U_1 \le U_2\right) = P\left(V_1 + \varepsilon_1 \le V_2 + \varepsilon_2\right) = P\left(\varepsilon_2 - \varepsilon_1 \ge V_1 - V_2\right) \quad \text{(B.7)}$$

or otherwise as:

$$P_1 = \Phi\left(\frac{V_1 - V_2}{\sigma}\right) \quad \text{(B.8)}$$

where $\sigma^2 = \sigma_1^2 + \sigma_2^2 - 2\sigma_{12}$ according to the variance-covariance matrix:

$$\Sigma = \begin{bmatrix} \sigma_1^2 & \sigma_{12} \\ \sigma_{12} & \sigma_2^2 \end{bmatrix} \quad \text{(B.9)}$$

In the case of multiple alternatives, however, evaluation of choice probabilities can be computationally intractable (Prashker & Bekhor, 2004; Ben-Akiva & Bierlaire, 1999); this has led some researchers to propose methods to deal with this shortcoming (e.g. Rosa & Maher, 2002; Bolduc, 1999; Sheffi, 1985). In addition, difficulty arises when defining the covariance matrix and, in particular, the relation between the error variance and network parameters. Sheffi & Powell (1982) related it with links' fixed characteristics such as free flow travel time or length, while Yai et al. (1997) assumed a covariance matrix based on the common length of overlapping routes.

In this context, MNP's drawbacks can be summarized in: (a) the complexity of the variance-covariance matrix, and (b) the absence of a closed-form expression for the probabilities. The latter problem is often overcome with the use of Monte-Carlo simulation (Ben-Akiva & Bierlaire, 1999). As for the first shortcoming, Ben-Akiva & Bierlaire (1999) note that complexity can be reduced in the case where "path utilities are link-additive, the variance of link utility is proportional to the utility itself, and the covariance of utilities of two different links is zero".

A.3 The hybrid logit model

While the MNP model assumes normal distribution for the error terms of the utility function and the MNL model considers them to be independently and identically distributed (iid) Gumbel variables, the literature attempted to bridge the gap between the two by proposing appropriate formulations with a combination of Gaussian and Gumbel error terms. The models developed by McFadden & Train (2000) and Ben-Akiva & Bolduc (1996) belong to this category and are referred to as the mixed logit model by the first and as the MNP with LK or simply LK model by the second.

The generalized, factor analytic formulation of random utility can be expressed as follows (Ben-Akiva & Bierlaire, 1999):

$$U_n = V_n + \varepsilon_n = V_n + F_n \zeta_n \quad \text{(B.10)}$$

where U_n is a $(J_n \times 1)$ vector of utilities, V_n is a $(J_n \times 1)$ vector of deterministic utilities, ε_n is a $(J_n \times 1)$ vector of random terms, ζ_n is a $(M \times 1)$ vector of factors which are iid standard normal distributed, and F_n is a $(J_n \times M)$ matrix of loadings that map the factors to the random utility vector. The above formulation is very general. If $M = J$ (i.e. the number of alternatives in the universal set), matrix F can be defined as the Cholesky factor of the variance-covariance matrix Σ, such that $\Sigma = FF^T$. In this case, F_n is obtained by removing the rows associated with unavailable alternatives.

The MNP with LK or hybrid logit model was first developed by Ben-Akiva & Bolduc (1996) as a combination of the MNL and MNP model. The utility function has the following form:

$$U_{in} = V_{in} + \xi_{in} + u_{in} \tag{B.11}$$

where ξ_{in} and u_{in} correspond to the normally distributed variables and the iid distributed Gumbel variables respectively. If ξ_{in} are known, the model collapses to the MNL model. Given that:

$$P\left(i \middle| C_n, \xi_n\right) = \frac{e^{V_{in}+\xi_{in}}}{\sum_{j \in C_n} e^{V_{jn}+\xi_{jn}}} \tag{B.12}$$

where $\xi_n = \left[\xi_1, ..., \xi_j\right]^T$ is the vector of random terms, the probability of choosing route i can be expressed as:

$$P\left(i \middle| C_n\right) = \int_{\xi_n} P\left(i \middle| C_n, \xi_n\right) f(\xi_n) d\xi_n \tag{B.13}$$

where $f(\xi_n)$ is the probability density function of ξ_n. When $f(\xi_n)$ is the multivariate normal distribution, the model is a generalization of the MNP, but other distributions may also be used.

A.4 Additional references (not included in the main text)

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Appendix B

B.1 Accessibility

Accessibility can be used in a variety of concepts: investigate the interaction of human systems with the built environment, propose changes in land-use patterns or the transportation system or identify social inequities (Bhat et al., 2000). In addition, some researchers (Geurs & van Wee, 2004; Morris et al., 1979; Weibull, 1976) have proposed several criteria regarding the form of accessibility measures. In general, different types of classification have been proposed in the literature. Geurs & Ritsema van Eck (2001) have distinguished between infrastructure-based, activity-based and utility-based measures. Bhat et al. (2000) refer to five types of indices: spatial separation, cumulative opportunity, gravity, logsum / utility and time-space ones. Scheurer & Curtis (2007) use a seven-category classification: spatial separation, contour, gravity, competition, time-space, utility and network measures.

Spatial separation (or otherwise infrastructure-based) measures account only for the distances between locations, ignoring land-use patterns, location attractiveness and forms of travel impedance. As such, they are useful for analyzing network structures. A more complex structure of this type of measures has been proposed by Baradaran & Ramjerdi (2001) who use the travel cost approach. In this case, distance can be replaced by travel time, travel cost, travel reliability and so forth.

Cumulative opportunities (or contour) measures define a time or distance threshold and enumerate the potential activities within that threshold. The measure incorporates land-use patterns but according to Scheurer & Curtis (2007) exhibits some shortcomings. First, the measure does not differentiate between opportunities in the same contour even though travel times may vary significantly. Second, the measure does not take into account the individual perspective but assumes that all opportunities are equally attractive. Third, thresholds are defined arbitrarily and do not necessarily correspond to the actual user perspective.

Gravity (or potential accessibility) measures also use an attraction as well as a separation factor. But, as opposed to the cumulative opportunities measures which use a discrete time / distance threshold, gravity measures use a continuous measure which discounts opportunities as time / distance from the origin increases. This is done with the use of a distance-decay function. Even though improved, the measure still lacks understanding of individual preferences and treats all travelers equally.

Competition (inverse balancing factor) measures account for competition factors when estimating accessibility. van Wee et al. (2001) argue that cumulative opportunities and gravity measures favor centralization of activities; however, there is an upper limit from which centralization can actually lead to accessibility decrease. For that reason, van Wee et al. (2001) incorporate competition effects; each zone is assessed on the basis of its attractiveness within a time / distance threshold; then, destination zones are assessed for their capacity for an activity and in relation to neighboring zones and the results are included in the measure of the original zone. However, the complexity of the model limits its applicability.

Utility measures account for the individual perceived utility for different travel choices. The measure may come in different forms: as a measure of economic utility, an indicator of social equity or a behavioral indicator (Scheurer & Curtis, 2007). Bhat et al. (2000) point out the importance of determining the right set of choices as well as the inability of the measure to capture the impact of new choices on travel behavior. Geurs & Ritsema van Eck (2001) argue in favor of the sound theoretical and the behavioral basis of the model, but mention the difficulties in interpreting the results and comparing different utility functions.

Time-space measures add a time dimension in accessibility estimation (time budget or time-space paths) (Scheurer & Curtis, 2007). Bhat et al. (2000) identify three types of time constraints: capability, coupling and authority constraints. This measure offers better evaluation of the trip chaining process (Wang & Timmermans, 1996) as well as understanding of different accessibility levels faced by members of the same household (Kwan, 1998). However, the information required is usually not available (Geurs & Ritsema van Eck, 2001; Bhat et al., 2000), while time constraints do not offer full interpretation of individual travel choices (Wang & Timmermans, 1996).

Finally, *network measures* investigate network-level accessibility. Porta et al. (2006a; 2006b) distinguish between the primal and the dual approach. In the primal approach, roadways are identified as edges and intersections as nodes. The exact opposite is valid for the dual approach. The primal approach is able to capture distance (or any other travel impedance measure); the dual approach estimates path length from the number of traversed edges (Scheurer & Curtis, 2007). There are a number of indices derived from both approaches: node degree, clustering coefficient, degree centrality, closeness centrality etc. As Scheurer & Curtis (2007) note, experiments conducted by Porta et al. (2006a, 2006b) on real urban networks proved the superiority of the primal approach. This can be attributed to the vagueness of the dual approach as well as its vulnerability in defining node (i.e. roadway) continuity.

B.2 Additional references (not included in the main text)

Kwan, M.-P. (1998). Space-Time and Integral Measures of Individual Accessibility: A Comparative Analysis Using a Point-based Framework. *Geographical Analysis*, *30*(3), 191-216.

Porta, S., Crucitti, P. & Latora, V. (2006a). The Network Analysis of Urban Streets: A Dual Approach. *Physica A: Statistical Mechanics and its Applications*, *369*(2), 853-866.

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van Wee, B., Hagoort, M. & Annema, J. A. (2001). Accessibility Measures with Competition. *Journal of Transport Geography*, *9*(3), 199-208.

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Appendix C

C.1 Results

Hereinafter are presented the results of the analyses that were not included in the main text. In this respect **Tables C.1** to **C.7** summarize the results for: (a) the link capacity degradation scenario (*15*-node network with $c_{ij} = 500 veh/h/lane$) (**Table C.1**), (b) the complete component failure scenario (*14*-node network with $c_{ij} = 900 veh/h/lane$) (**Table C.2**), (c) the increased level of stochasticity scenario (*15*-node network with $c_{ij} = 900 veh/h/lane$ and $\theta = 0.01$) (**Table C.3**), (d) the *15*-node network with $c_{ij} = 900 veh/h/lane$ under DUE analysis (**Table C.4**), (e) the *15*-node network with $c_{ij} = 900 veh/h/lane$ under SO analysis (**Table C.5**), (f) the increased path dissimilarity scenario (*15*-node network with $c_{ij} = 900 veh/h/lane$ and $P = 0.5$) (**Table C.6**), and (g) the demand augmentation scenario (*15*-node network with $c_{ij} = 900 veh/h/lane$ and $q^{rs'} = 2.0 q^{rs}$) (**Table C.7**). As such, **Tables C.1** to **C.7** present: (a) the OF value best runs for each of the six CR / MR combinations investigated (OF, TNTT, SD and OD-A values), (b) the average OF value for each of the CR / MR combinations, (c) the average OF value of all runs, (d) the average OF and OF component values for the best runs (with individual standard deviations and coefficients of variation additionally calculated), and (e) the OF and OF terms' deviation from average for the absolutely best experiment. In addition, **Table C.8** presents the relative and cumulative relative lane-changing frequency of the network's links, as these are derived from the analyses conducted over the *15*-node network with $c_{ij} = 900 veh/h/lane$. Subsequently, **Tables C.9** and **C.10** distinguish between the results of **Table C.8** by providing the respective lane-changing frequency values corresponding to the two clusters formed by the aforementioned solutions.

Table C.1 Analysis results for the *15*-node network with c_{ij} = 500veh/h/lane

	Crossover rate	Mutation rate	Objective function best runs					Objective function (average of all runs)
			Total network travel time	Satisfied demand	OD-pair accessibility		Objective function	
					Distance-based	Travel time-based		
15 nodes, c_{ij} = 500veh/h/lane	0.70	0.03	0.015645	0.248130	0.272850	0.030585	0.070950	0.148683
	0.80	0.03	0.017466	0.238944	0.271306	0.031816	0.081645	0.135036
	0.90	0.03	0.015612	0.244470	0.272820	0.030387	0.074349	0.138724
	0.70	0.05	0.015757	0.246637	0.271590	0.031901	0.072612	0.138618
	0.80	0.05	0.011947	0.244103	0.289854	0.019598	0.077295	0.135300
	0.90	**0.05**	**0.016538**	**0.249625**	**0.257760**	**0.028623**	**0.053297**	**0.141306**
	Average		0.015494	0.245318	0.272697	0.028818	0.071691	**0.139611**
	Standard deviation		0.001716	0.003441	0.009315	0.004265	0.008919	0.004591
	Coefficient of variation (%)		11.075580	1.402488	3.416025	14.798873	12.440730	3.288509
	Best experiment		0.016538	0.249625	0.257760	0.028623	0.053297	na
	Deviation from average (%)		6.738710	1.755529	-5.477279	-0.677849	-25.657546	na

Table C.2 Analysis results for the *14*-node network with c_{ij} = 900veh/h/lane

	Crossover rate	Mutation rate	Objective function best runs					Objective function (average of all runs)
			Total network travel time	Satisfied demand	OD-pair accessibility		Objective function	
					Distance-based	Travel time-based		
14 nodes, c_{ij} = 900veh/h/lane	0.70	0.03	0.014515	0.235036	0.300672	0.026787	0.106937	0.159946
	0.80	0.03	0.021536	0.242481	0.266447	0.037496	0.082999	0.130874
	0.90	0.03	0.019007	0.239972	0.266129	0.034169	0.079333	0.139834
	0.70	0.05	0.010828	0.246129	0.283576	0.022249	0.070524	0.150803
	0.80	0.05	0.019661	0.238660	0.266807	0.033814	0.081622	0.130165
	0.90	**0.05**	**0.016375**	**0.240574**	**0.264860**	**0.029733**	**0.070393**	**0.149323**
	Average		0.016987	0.240475	0.274748	0.030708	0.081968	**0.143491**
	Standard deviation		0.003567	0.003394	0.013254	0.005092	0.012224	0.010866
	Coefficient of variation (%)		20.999149	1.411518	4.824026	16.582863	14.912898	7.572328
	Best experiment		0.016375	0.240574	0.264860	0.029733	0.070393	na
	Deviation from average (%)		-3.605103	0.041110	-3.599096	-3.174710	-14.120887	na

Table C.3 Analysis results for the *15*-node network with c_{ij} = 900veh/h/lane: θ = 0.01 scenario

	Crossover rate	Mutation rate	Objective function best runs					Objective function (average of all runs)
			Total network travel time	Satisfied demand	OD-pair accessibility		Objective function	
					Distance-based	Travel time-based		
θ = 0.5	0.70	0.03	0.026088	0.237699	0.271438	0.042691	0.102519	0.174284
	0.80	0.03	0.028343	0.242574	0.290857	0.039370	0.115996	0.177544
	0.90	**0.03**	**0.019749**	**0.235853**	**0.289497**	**0.027637**	**0.101029**	**0.180112**
	0.70	0.05	0.025356	0.230109	0.273447	0.043724	0.112419	0.165641
	0.80	0.05	0.018994	0.251173	0.325866	0.023094	0.116781	0.148371
	0.90	0.05	0.020207	0.230920	0.301208	0.034689	0.125184	0.171247
	Average		0.023123	0.238055	0.292052	0.035201	0.112321	**0.169533**
	Standard deviation		0.003605	0.007205	0.018286	0.007640	0.008391	0.010524
	Coefficient of variation (%)		15.589090	3.026811	6.261117	21.702805	7.470515	6.207905
	Best experiment		0.019749	0.235853	0.289497	0.027637	0.101029	na
	Deviation from average (%)		-14.590492	-0.924693	-0.875029	-21.487969	-10.053292	na

Table C.4 Analysis results for the *15*-node network with c_{ij} = 900veh/h/lane: DUE analysis

	Crossover rate	Mutation rate	Objective function best runs					Objective function (average of all runs)
			Total network travel time	Satisfied demand	OD-pair accessibility		Objective function	
					Distance-based	Travel time-based		
DUE	**0.70**	**0.03**	**0.000233**	**0.238423**	**0.245875**	**0.017807**	**0.025491**	**0.045236**
	0.80	0.03	0.000254	0.233710	0.246124	0.017099	0.029767	0.038644
	0.90	0.03	0.000058	0.245393	0.256128	0.018173	0.028966	0.053226
	0.70	0.05	0.000159	0.250991	0.253368	0.026450	0.028986	0.070682
	0.80	0.05	0.000276	0.235227	0.245093	0.018077	0.028219	0.049800
	0.90	0.05	0.000169	0.243750	0.254685	0.021273	0.032377	0.052657
	Average		0.000191	0.241249	0.250212	0.019813	0.028968	**0.051707**
	Standard deviation		0.000073	0.006047	0.004595	0.003248	0.002038	0.009827
	Coefficient of variation (%)		38.326578	2.506694	1.836509	16.390773	7.033918	19.004758
	Best experiment		0.000233	0.238423	0.245875	0.017807	0.025491	na
	Deviation from average (%)		21.595192	-1.171322	-1.733528	-10.126182	-12.001967	na

Table C.5 Analysis results for the *15*-node network with c_{ij} = 900veh/h/lane: SO analysis

	Crossover rate	Mutation rate	Objective function best runs					Objective function (average of all runs)
			Total network travel time	Satisfied demand	OD-pair accessibility		Objective function	
					Distance-based	Travel time-based		
SO	0.70	0.03	0.010586	0.241356	0.250783	0.018045	0.038058	0.040514
	0.80	0.03	0.010563	0.242450	0.257539	0.017996	0.043648	0.045609
	0.90	0.03	0.012563	0.246891	0.259540	0.019856	0.045068	0.046893
	0.70	0.05	0.010053	0.240986	0.293043	0.018546	0.043564	0.045430
	0.80	**0.05**	**0.007126**	**0.240727**	**0.243910**	**0.010546**	**0.020854**	**0.037550**
	0.90	0.05	0.010436	0.243726	0.261648	0.018896	0.047254	0.048062
	Average		0.010221	0.242689	0.261077	0.017314	0.039741	**0.044010**
	Standard deviation		0.001602	0.002134	0.015480	0.003090	0.008891	0.003725
	Coefficient of variation (%)		15.669691	0.879153	5.929134	17.846489	22.371300	8.463738
	Best experiment		0.007126	0.240727	0.243910	0.010546	0.020854	na
	Deviation from average (%)		-30.285504	-0.808447	-6.575602	-39.090106	-47.525197	na

Table C.6 Analysis results for the *15*-node network with c_{ij} = 900veh/h/lane: P = 0.5 scenario

	Crossover rate	Mutation rate	Objective function best runs					Objective function (average of all runs)
			Total network travel time	Satisfied demand	OD-pair accessibility		Objective function	
					Distance-based	Travel time-based		
P = 0.5	0.70	0.03	0.016635	0.235739	0.274703	0.029727	0.085326	0.141438
	0.80	**0.03**	**0.007596**	**0.248599**	**0.250601**	**0.012171**	**0.021769**	**0.136403**
	0.90	0.03	0.015536	0.237023	0.296953	0.026098	0.101564	0.136982
	0.70	0.05	0.013441	0.238896	0.302292	0.025513	0.102350	0.152428
	0.80	0.05	0.011704	0.249463	0.273692	0.021412	0.057344	0.141557
	0.90	0.05	0.014036	0.240930	0.302809	0.026102	0.102017	0.141693
	Average		0.013158	0.241775	0.283508	0.023504	0.078395	**0.141750**
	Standard deviation		0.002934	0.005380	0.018986	0.005613	0.029906	0.005252
	Coefficient of variation (%)		22.296858	2.225314	6.696974	23.882849	38.148247	3.704813
	Best experiment		0.007596	0.248599	0.250601	0.012171	0.021769	na
	Deviation from average (%)		-42.269157	2.822364	-11.607275	-48.218098	-72.231776	na

Table C.7 Analysis results for the *15*-node network with c_{ij} = 900veh/h/lane: $q^{rs'}$ = 2.0q^{rs} scenario

	Crossover rate	Mutation rate	Objective function best runs					Objective function (average of all runs)
			Total network travel time	Satisfied demand	OD-pair accessibility		Objective function	
					Distance-based	Travel time-based		
***P* = 0.5**	0.70	0.03	0.098634	0.246146	0.294975	0.034836	0.098634	0.138634
	0.80	0.03	0.100076	0.242337	0.301383	0.026915	0.100076	0.146061
	0.90	0.03	0.014462	0.242468	0.301469	0.027662	0.101125	0.139130
	0.70	0.05	0.103808	0.237894	0.300972	0.026737	0.103808	0.133867
	0.80	0.05	0.102279	0.241223	0.297185	0.030117	0.102279	0.140394
	0.90	**0.05**	**0.011684**	**0.238552**	**0.301552**	**0.022841**	**0.097525**	**0.139183**
	Average		0.071824	0.241437	0.299589	0.028185	0.100574	**0.139545**
	Standard deviation		0.041582	0.002738	0.002569	0.003663	0.002120	0.003572
	Coefficient of variation (%)		57.895060	1.133922	0.857358	12.997162	2.108152	2.559711
	Best experiment		0.011684	0.238552	0.301552	0.022841	0.097525	na
	Deviation from average (%)		-83.732693	-1.194863	0.655032	-18.957772	-3.031761	na

Table C.8 Relative and cumulative relative lane-changing frequency of each of the network's links for the *15*-node network with c_{ij} = 900veh/h/lane

From node	To node	Relative lane-changing frequency (%)				Cumulative relative lane-changing frequency (%)
		-2 lanes	-1 lane	+1 lane	+2 lanes	
1	2	0.00	0.00	0.00	0.00	0.00
1	3	0.00	0.00	0.00	0.00	0.00
1	5	0.00	0.00	0.00	0.00	0.00
2	1	0.00	0.00	0.00	0.00	0.00
2	3	0.00	30.00	10.00	0.00	40.00
2	9	0.00	0.00	3.33	0.00	3.33
3	1	0.00	0.00	0.00	0.00	0.00
3	2	0.00	10.00	30.00	0.00	40.00
3	6	0.00	6.67	26.67	0.00	33.33
3	7	0.00	38.33	8.33	0.00	46.67
4	5	0.00	1.67	8.33	0.00	10.00
4	6	0.00	0.00	0.00	0.00	0.00
4	14	0.00	16.67	6.67	0.00	23.33
5	1	0.00	0.00	0.00	0.00	0.00
5	4	0.00	8.33	1.67	0.00	10.00
5	14	0.00	0.00	0.00	0.00	0.00
6	3	0.00	26.67	6.67	0.00	33.33
6	4	0.00	0.00	0.00	0.00	0.00
6	10	0.00	8.33	5.00	0.00	13.33
6	13	0.00	0.00	8.33	0.00	8.33
7	3	0.00	8.33	38.33	0.00	46.67
7	9	0.00	15.00	16.67	0.00	31.67
7	10	0.00	56.67	35.00	0.00	91.67
8	9	0.00	10.00	5.00	0.00	15.00
8	10	11.67	21.67	26.67	5.00	65.00
8	12	0.00	16.67	33.33	0.00	50.00
9	2	0.00	3.33	0.00	0.00	3.33
9	7	0.00	16.67	15.00	0.00	31.67
9	8	0.00	5.00	10.00	0.00	15.00
10	6	0.00	5.00	8.33	0.00	13.33
10	7	0.00	35.00	56.67	0.00	91.67
10	8	5.00	26.67	21.67	11.67	65.00
10	11	0.00	0.00	0.00	0.00	0.00
11	10	0.00	0.00	0.00	0.00	0.00
11	12	0.00	21.67	40.00	0.00	61.67
11	13	0.00	0.00	0.00	0.00	0.00
12	8	0.00	33.33	16.67	0.00	50.00
12	11	0.00	40.00	21.67	0.00	61.67
12	15	0.00	0.00	0.00	0.00	0.00
13	6	0.00	8.33	0.00	0.00	8.33
13	11	0.00	0.00	0.00	0.00	0.00
13	14	0.00	0.00	0.00	0.00	0.00
13	15	0.00	21.67	40.00	0.00	61.67
14	4	0.00	6.67	16.67	0.00	23.33
14	5	0.00	0.00	0.00	0.00	0.00
14	13	0.00	0.00	0.00	0.00	0.00
15	12	0.00	0.00	0.00	0.00	0.00
15	13	0.00	40.00	21.67	0.00	61.67

Table C.9 Relative and cumulative relative lane-changing frequency of each of the network's links for the first cluster of solutions of the *15*-node network with c_{ij} = 900veh/h/lane

From node	To node	Relative lane-changing frequency (%)				Cumulative relative lane-changing frequency (%)
		-2 lanes	-1 lane	+1 lane	+2 lanes	
1	2	0.00	0.00	0.00	0.00	0.00
1	3	0.00	0.00	0.00	0.00	0.00
1	5	0.00	0.00	0.00	0.00	0.00
2	1	0.00	0.00	0.00	0.00	0.00
2	3	0.00	13.33	6.67	0.00	20.00
2	9	0.00	0.00	3.33	0.00	3.33
3	1	0.00	0.00	0.00	0.00	0.00
3	2	0.00	6.67	13.33	0.00	20.00
3	6	0.00	1.67	11.67	0.00	13.33
3	7	0.00	18.33	3.33	0.00	21.67
4	5	0.00	1.67	1.67	0.00	3.33
4	6	0.00	0.00	0.00	0.00	0.00
4	14	0.00	11.67	6.67	0.00	18.33
5	1	0.00	0.00	0.00	0.00	0.00
5	4	0.00	1.67	1.67	0.00	3.33
5	14	0.00	0.00	0.00	0.00	0.00
6	3	0.00	11.67	1.67	0.00	13.33
6	4	0.00	0.00	0.00	0.00	0.00
6	10	0.00	5.00	3.33	0.00	8.33
6	13	0.00	0.00	6.67	0.00	6.67
7	3	0.00	3.33	18.33	0.00	21.67
7	9	0.00	8.33	11.67	0.00	20.00
7	10	0.00	31.67	21.67	0.00	53.33
8	9	0.00	5.00	3.33	0.00	8.33
8	10	6.67	13.33	15.00	3.33	38.33
8	12	0.00	11.67	28.33	0.00	40.00
9	2	0.00	3.33	0.00	0.00	3.33
9	7	0.00	11.67	8.33	0.00	20.00
9	8	0.00	3.33	5.00	0.00	8.33
10	6	0.00	3.33	5.00	0.00	8.33
10	7	0.00	21.67	31.67	0.00	53.33
10	8	3.33	15.00	13.33	6.67	38.33
10	11	0.00	0.00	0.00	0.00	0.00
11	10	0.00	0.00	0.00	0.00	0.00
11	12	0.00	15.00	30.00	0.00	45.00
11	13	0.00	0.00	0.00	0.00	0.00
12	8	0.00	28.33	11.67	0.00	40.00
12	11	0.00	30.00	15.00	0.00	45.00
12	15	0.00	0.00	0.00	0.00	0.00
13	6	0.00	6.67	0.00	0.00	6.67
13	11	0.00	0.00	0.00	0.00	0.00
13	14	0.00	0.00	0.00	0.00	0.00
13	15	0.00	15.00	30.00	0.00	45.00
14	4	0.00	6.67	11.67	0.00	18.33
14	5	0.00	0.00	0.00	0.00	0.00
14	13	0.00	0.00	0.00	0.00	0.00
15	12	0.00	0.00	0.00	0.00	0.00
15	13	0.00	30.00	15.00	0.00	45.00

Table C.10 Relative and cumulative relative lane-changing frequency of each of the network's links for the second cluster of solutions of the *15*-node network with c_{ij} = 900veh/h/lane

From node	To node	Relative lane-changing frequency (%)				Cumulative relative lane-changing frequency (%)
		-2 lanes	-1 lane	+1 lane	+2 lanes	
1	2	0.00	0.00	0.00	0.00	0.00
1	3	0.00	0.00	0.00	0.00	0.00
1	5	0.00	0.00	0.00	0.00	0.00
2	1	0.00	0.00	0.00	0.00	0.00
2	3	0.00	16.67	3.33	0.00	20.00
2	9	0.00	0.00	0.00	0.00	0.00
3	1	0.00	0.00	0.00	0.00	0.00
3	2	0.00	3.33	16.67	0.00	20.00
3	6	0.00	5.00	15.00	0.00	20.00
3	7	0.00	20.00	5.00	0.00	25.00
4	5	0.00	0.00	6.67	0.00	6.67
4	6	0.00	0.00	0.00	0.00	0.00
4	14	0.00	5.00	0.00	0.00	5.00
5	1	0.00	0.00	0.00	0.00	0.00
5	4	0.00	6.67	0.00	0.00	6.67
5	14	0.00	0.00	0.00	0.00	0.00
6	3	0.00	15.00	5.00	0.00	20.00
6	4	0.00	0.00	0.00	0.00	0.00
6	10	0.00	3.33	1.67	0.00	5.00
6	13	0.00	0.00	1.67	0.00	1.67
7	3	0.00	5.00	20.00	0.00	25.00
7	9	0.00	6.67	3.33	0.00	10.00
7	10	0.00	23.33	13.33	0.00	36.67
8	9	0.00	5.00	1.67	0.00	6.67
8	10	5.00	8.33	10.00	1.67	25.00
8	12	0.00	5.00	5.00	0.00	10.00
9	2	0.00	0.00	0.00	0.00	0.00
9	7	0.00	3.33	6.67	0.00	10.00
9	8	0.00	1.67	5.00	0.00	6.67
10	6	0.00	1.67	3.33	0.00	5.00
10	7	0.00	13.33	23.33	0.00	36.67
10	8	1.67	10.00	8.33	5.00	25.00
10	11	0.00	0.00	0.00	0.00	0.00
11	10	0.00	0.00	0.00	0.00	0.00
11	12	0.00	6.67	10.00	0.00	16.67
11	13	0.00	0.00	0.00	0.00	0.00
12	8	0.00	5.00	5.00	0.00	10.00
12	11	0.00	10.00	6.67	0.00	16.67
12	15	0.00	0.00	0.00	0.00	0.00
13	6	0.00	1.67	0.00	0.00	1.67
13	11	0.00	0.00	0.00	0.00	0.00
13	14	0.00	0.00	0.00	0.00	0.00
13	15	0.00	6.67	10.00	0.00	16.67
14	4	0.00	0.00	5.00	0.00	5.00
14	5	0.00	0.00	0.00	0.00	0.00
14	13	0.00	0.00	0.00	0.00	0.00
15	12	0.00	0.00	0.00	0.00	0.00
15	13	0.00	10.00	6.67	0.00	16.67