SVEUČILIŠTE U ZAGREBU
FAKULTET PROMETNIH ZNANOSTI
ZAVOD ZA INTELIGENTNE TRANSPORTNE SUSTAVE

PROBLEM USMJERAVANJA ELEKTRIČNIH VOZILA

KVALIFIKACIJSKI DOKTORSKI ISPIT

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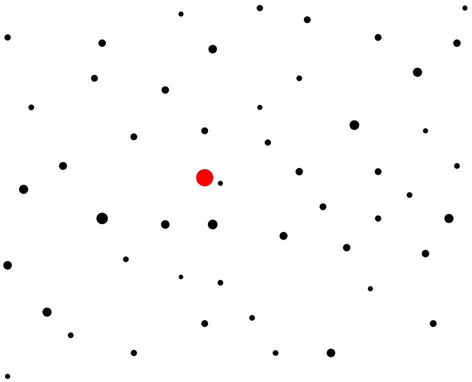
19. srpnja 2018.

Pregled

Problem usmjeravanja vozila

- Problem usmjeravanja vozila (engl. *Vehicle Routing Problem*, VRP, [1])
  - ULAZ: n geografski raspršenih korisnika, homogena flota m vozila
  - IZLAZ: Rute s najmanjim mogućim troškom koje poslužuju sve korisnike uz ograničenja
- Generalizacija dobro poznatog problema trgovačkog putnika (engl. *Traveling Salesman Problem*, TSP)

Problem usmjeravanja vozila

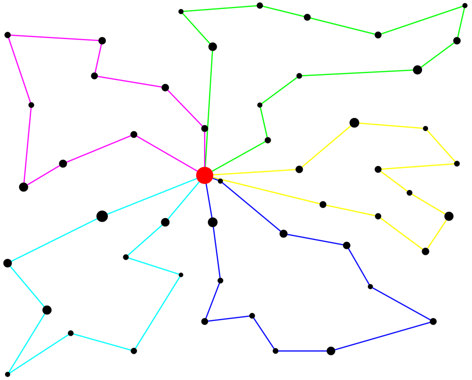


Slika: CVRP instanca *CMT: vrpnc1*, 50 korisnika, [4]

Problem usmjeravanja vozila

- Kombinatorna eksplozija $n = 50$
  - Broj kombinacija za posluživanje jednim vozilom: $50! = 3.04 \cdot 10^{64}$
  - Izvršavanje jedne operacije u Planck-ovom vremenu $t_P = 5.39 \cdot 10^{-44}$ s
  - Vrijeme za provjeru svih kombinacija: $T = 1.63 \cdot 10^{21}$ s
  - Procijenjena starost svemira $13.7 \cdot 10^{9}$ godina $= 4.32 \cdot 10^{17}$ s

Problem usmjeravanja vozila



Slika: CVRP: $m = 5$, $D = 524.61$

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- Generalizacija dobro poznatog problema trgovačkog putnika (engl. *Traveling Salesman Problem*, TSP)
- NP-težak problem
- U posljednjih 50 godina razmatrane su brojne verzije originalnog problema, [2, 3]:
    - CVRP, VRPTW, VRPPD, VRPB, TD-VRPTW, DVRP, PVRP, Open VRP, MFVRP, PRP, GVRP, E-VRP i dr.

Električna vozila

- Konvencionalna vozila s motorima s unutarnjim izgaranjem zagađuju okoliš te ovise o ograničenim resursima fosilnih goriva

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- Električna vozila su među najčišćim načinima transporta
  - Napajanje električnom energijom → obnovljivi izvori energije
  - Nemaju lokalnu emisiju stakleničkih plinova
  - Proizvode minimalnu buku

Električna vozila - ograničenja i problemi

- Domet električnih vozila:
  - 100 - 200 km → manja teretna vozila, [5, 6]
  - 85 - 528 km → 40 različitih vrsta električnih vozila, [7]

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- Češća potreba za punjenjem $\rightarrow$ povećanje radnih troškova i teže ostvarivanje pravovremene dostave, [9]

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- Visoka kupovna cijena

Električna vozila - evaluacija i primjena

- Evaluacija uvođenja električne flote vozila, [10, 5, 11, 12, 13, 14, 9, 8]
  - *Are ECVs breaking even?* $\rightarrow$ analiza slučaja, [10]
    - 302 TEDi prodavaonice, radijus dostave $\approx$ 190 km
    - Stanice za punjenje na lokacijama korisnika
    - Jednak broj električnih i dizelskih vozila (50 vozila), te jednaka ukupna prijeđena udaljenost (19200 km)
    - Procijenjene uštede od 12 % do 32 %, 64000 – 500000 € godišnje
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- Primjena za tzv. *last-mile* dostavu, [14]
  - DHL, UPS, [15, 16, 6]

Razvoj E-VRP problema

1. (2011.) → mix VRPPD, [17]
   - Virtualne lokacije stanica za punjenje i heterogena flota vozila
2. (2011.) → *The Recharging VRP*, [18]
   - Stanice za punjenje na lokacijama korisnika s fiksnim vremenom punjenja
3. (2012.) → *Green VRP*, [19]
   - Napajanje alternativnim gorivima (biodizel, električna energija, etanol, vodik, metanol, prirodni plin i dr.)
   - Zasebne lokacije stanica za punjenje s fiksnim vremenom punjenja
4. (2014.) → *E-VRPTW*, [20]
   - Homogena flota električnih vozila
   - Zasebne lokacije stanica za punjenje s vremenom punjenja ovisnim o razini napunjenosti

E-VRPTW - model

- ULAZ
  - Homogena flota baterijskih električnih vozila s kapacitetom baterije Q, teretnim kapacitetom C i potrošnjom energije r
  - Korisnici koje je potrebno poslužiti: lokacija, potražnja q_i i vremenski prozor $[e_i, l_i]$
  - Stanice za punjenje (engl. *Charging Station*, CS): lokacija i brzina punjenja g
- PRETPOSTAVKE
  - Ravan teren
  - Konstantne brzine
  - Linearna karakteristika punjenja te punjenje do kraja
  - Zanemarivanje utjecaja tereta, otpora zraka i prijenosnog omjera

E-VRP - model

- Cjelobrojni mješoviti program
  - set korisnika $V = \{1, \ldots, N\}$, set posjeta stanicama za punjenje F' i čvorovi skladišta 0, $N+1$ (početak-kraj rute)

$$V'_{0,N+1} = V \cup F' \cup \{0\} \cup \{N+1\} \quad (1)$$

  - Potpuni graf

$$G = (V'_{0,N+1}, A) \Rightarrow A = \{(i,j) | i,j \in V'_{0,N+1}, i \neq j\} \quad (2)$$

  - Binarna varijabla

$$x_{ij} \in \{0,1\} \; \forall i \in V_0, j \in V'_{N+1}, i \neq j \quad (3)$$

  - Težine lukova:
    - Duljina d_{ij}
    - Vrijeme putovanja t_{ij}
    - Energetska potrošnja e_{ij}
    - Brzina v_{ij}

E-VRPTW - Funkcije cilja

- Hijerarhijska funkcija cilja, [3, 20, 21]
  1. Minimizacija broja vozila:

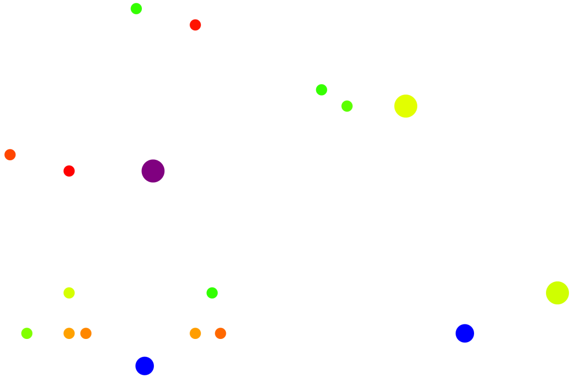
$$\min \sum_{j \in V'_{N+1}} x_{0j} \tag{4}$$

  2. Minimizacija ukupne prijeđene udaljenosti:

$$\min \sum_{i \in V'_0, j \in V'_{N+1} i \neq j} d_{ij} x_{ij} \tag{5}$$

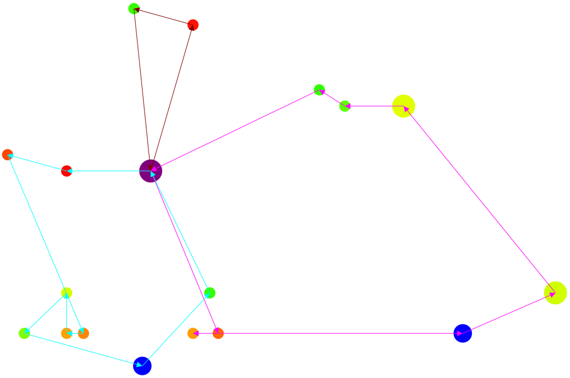
- Ukupni troškovi, [22, 23, 24, 25, 14, 10, 26, 27]
  - Kupovina vozila, energetska potrošnja (cijena el. en.), troškovi zamjena baterija (≈ 240 000 km, 600 $ po kWh, [23]), radni sati zaposlenika
- Vrijeme putovanja, [28]
- Emisija štetnih plinova → PRP, [29, 30]

E-VRPTW - primjer



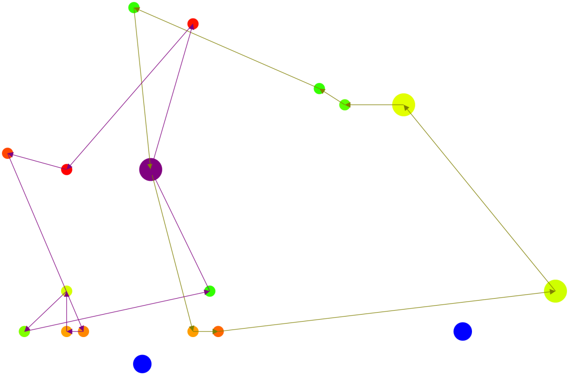
Slika: Instanca *c106C15*: 15 korisnika, 2 CS, [20]

E-VRPTW - primjer



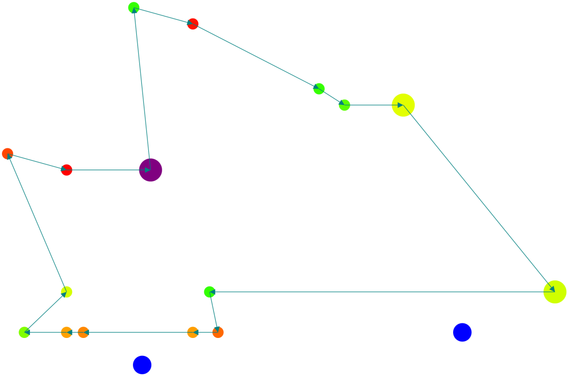
Slika: E-VRPTW: $m = 3$, $D = 275.13$

E-VRPTW - primjer



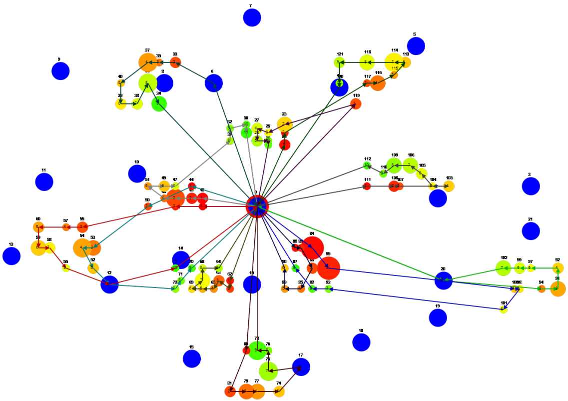
Slika: VRPTW: $m = 2$, $D = 274.35$

E-VRPTW - primjer



Slika: CVRP: $m = 1$, $D = 196.03$

E-VRPTW - primjer



Slika: E-VRPTW: *c101*, 101 korisnik, 21 CS, $m = 12$, $D = 1053.58$, [20]

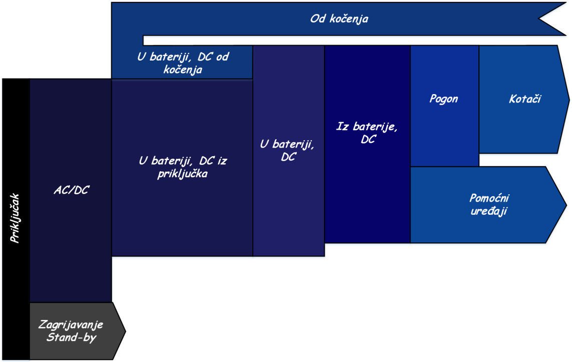
Inačice E-VRP problema

- Heterogena flota vozila → E-VRPTWMF, [22, 23, 14, 25, 31, 32]
  - Vozila se razlikuju u transportnom kapacitetu, veličini baterije, tipu motora i kupovnoj cijeni
- Strategije parcijalnog punjenja → E-VRPTW-PR, [33, 21, 34, 35, 36]
- Problem lociranja električnih punionica i rutiranja flote električnih vozila → E-LRP, [37, 38, 10, 21]
- Stanice za zamjenu baterija električnih vozila, [37, 38, 39]
- Rješavanje problema trgovačkog putnika → E-TSP, [40, 41, 42, 43]

Inačice E-VRP problema

- Stanice za punjenje, [25, 31, 32, 34]
  - Različite tehnologije punjenja, [34, 25]
    - Sporo $\rightarrow$ 3.6 KWh/h, $\approx$ 0.16 € $/KWh$, $6-8\ h$
    - Srednje $\rightarrow$ 20 KWh/h, $\approx$ 0.176 € $/KWh$, 2 h
    - Brzo $\rightarrow$ 45 KWh/h, $\approx$ 0.192 € $/KWh$, $20-30\ min$
  - Vrijeme rada stanice i vremenski ovisan trošak punjenja
  - Opterećenje energetske mreže
  - Broj dostupnih punjača za punjenje
- Nelinearna funkcija punjenja $\rightarrow$ E-VRP-NL, [35]
- Ograničenje stanja napunjenosti, [25, 31, 32]
- Vremenski ovisan E-VRP $\rightarrow$ TD-E-VRP, [44]
- Modeliranje energetske potrošnje, [9, 23, 14, 29]
  - Prevoženi teret, brzina, trenje kotrljanja, otpor zraka, nagib terena
  - Regenerativna energija, [14] $\rightarrow$ $5-15$ %, [45, 46]

Energetska potrošnja



Slika: Energetska potrošnja od priključka do kotača vozila, [14]

Energetska potrošnja

- Energetska potrošnja, [14, 23, 47]

$$F = \underbrace{mg \sin \alpha}_{\text{Nagib}} + \underbrace{c_r mg \cos \alpha}_{\text{Kotrljanje}} + \underbrace{0.5 c_d \rho A v^2}_{\text{Zrak}} + \underbrace{ma}_{\text{Ubrz.}} \tag{6}$$

$$P_b = \begin{cases} \mu_e(\mu_m F v + P_0), & \text{if } F \geq 0 \\ \begin{cases} 0, & \text{if } v \leq v_{min} \\ F v \mu_g + P_0, & \text{else} \end{cases}, & \text{if } F < 0 \end{cases} \tag{7}$$

- Podatkovno vođeni postupci, [48, 49, 50]

Pregled postupaka rješavanja E-VRP-a

- Egzaktni postupci - egzaktno rješavanje problema
- Heuristički - rješavanje na temelju specifičnog znanja
  - Konstruktivni
  - Unapređivački
- Metaheuristički - koriste se kako bi se nastavilo pretraživanje nakon prvog pronađenog lokalnog optimuma - tzv. *heuristike koje vode druge heuristike*
  - Susjedno orijentirani postupci
  - Populacijski postupci

Izvedivost rješenja

- Izvediva rješenja $\rightarrow$ u svakom koraku pretražuje se prostor izvedivih rješenja, [33, 51, 25, 31, 38]
- Ne-izvediva rješenja $\rightarrow$ dozvoljavaju se ne-izvediva rješenja kako bi se proširio prostor pretrage $\rightarrow$ funkcija cilja s koeficijentima kažnjavanja, [37, 26, 20, 23, 22]

$$f(S) = f_{dist}(S) + \alpha P_{cap}(S) + \beta P_{tw}(S) + \gamma P_{batt}(S) \qquad (8)$$

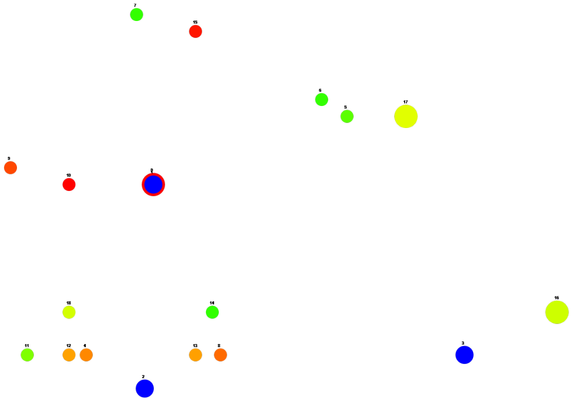
Egzaktni postupci

- Optimalno rješenje 50-100 korisnika, a novijim algoritmima i do 300 korisnika, [52]
- E-VRP primjena
  - metoda grananja i nagrade, [22, 53]
  - metoda grananja i ograđivanja, [40]
  - dinamičko programiranje → raspored CS u ruti, [10]

Konstruktivni heuristički postupci

- Stvaranje rješenja na pohlepan način, 10 - 15 % udaljeni od optimalnog rješenja, [54]
- Često se koriste za stvaranje početnog rješenja
- E-VRP primjena
  - *sweep* algoritam, [20]
  - *route-split* metoda, [35]
  - iterativno ubacivanje korisnika, [33, 22, 34, 23, 25]
  - *Clark*-ov i *Wright*-ov algoritam uštede, [19]
  - algoritam klasteriranja temeljen na gustoći, [19]

Konstruktivni heuristički postupci



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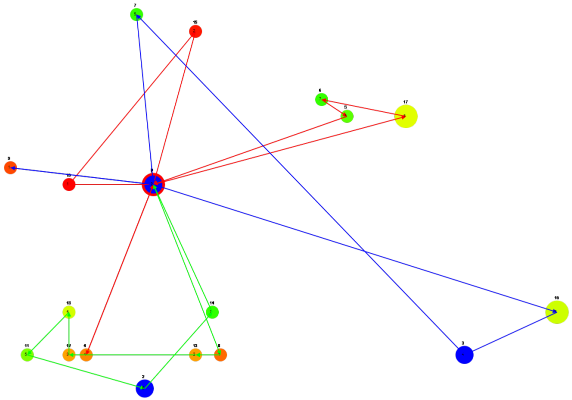
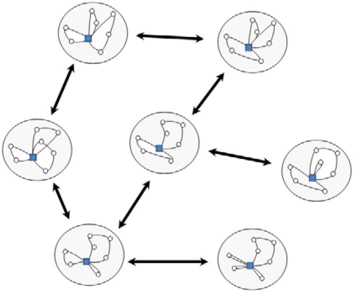


Slika: E-VRPTW početno rješenje iterativnim ubacivanjem korisnika, [34]: $m = 3$, $D = 431.74$

UNAPREĐIVAČKI HEURISTIČKI POSTUPCI

- Lokalno pretražuju susjedstvo problema perturbacijom rješenja



Slika: Susjedna rješenja, [55]

Unapređivački heuristički postupci

- Lokalno pretražuju susjedstvo problema perturbacijom rješenja
- Klasični kompozitni operatori susjedstva → sve dok se ne "zapne" u lokalnom optimumu
  - *2-opt, 3-opt, Or-opt, 2-opt*, relocate, exchange, CROSS-exchange*, [56, 54]
  - Operator ubacivanja i brisanja stanice za punjenje, [20, 34, 22]

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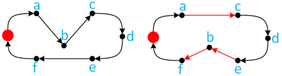
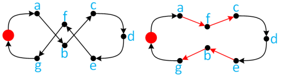
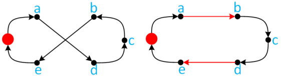


(A) *Relocate*

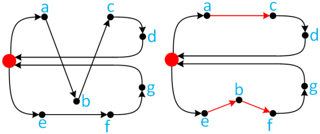


(B) *Exchange*



(C) *2Opt*

Slika: *Intra* operatori



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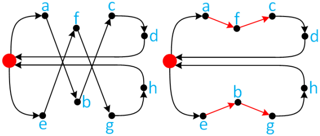

(B) *Exchange*

Slika: *Inter* operatori

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    - Vremenski prozori

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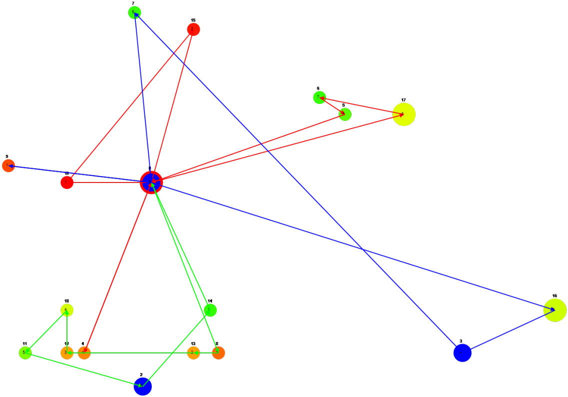
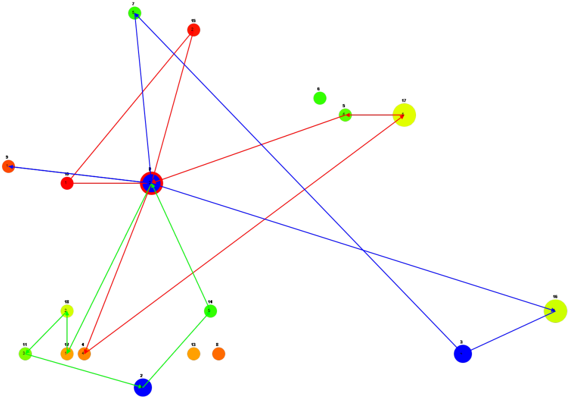
    - Vremenski prozori
- Pretraživanje velikog susjedstva, [57, 31, 32, 58] → uništavanje i popravljanje rješenja (engl. *ruin-recreate*)
  - 1 metoda uništavanja i 1 metoda popravljanja

Unapređivački heuristički postupci



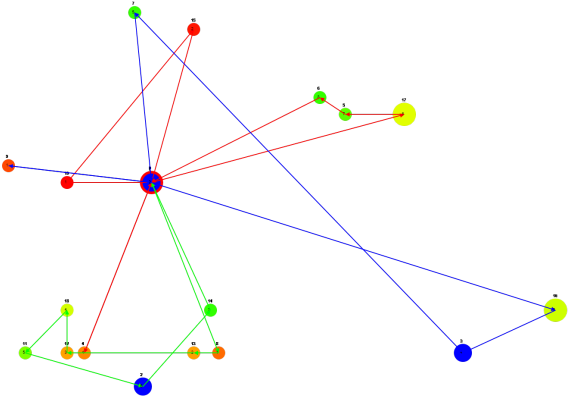
Slika: *E-VRPTW LNS* početno, $D = 431.74$

Unapređivački heuristički postupci



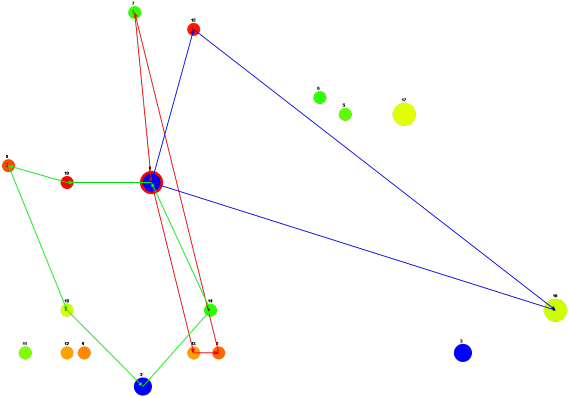
Slika: *E-VRPTW LNS ruin*, $D = 402.36$

unapređivački heuristički postupci



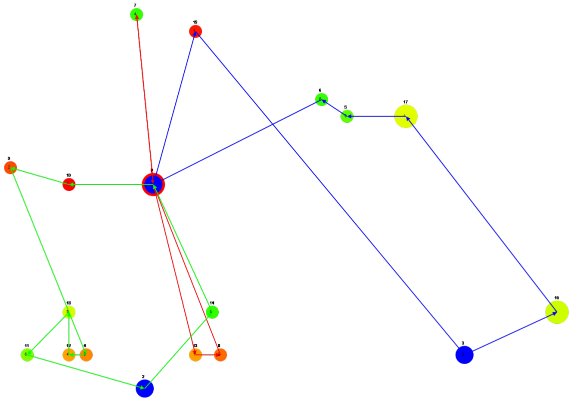
Slika: *E-VRPTW LNS recreate*, $D = 426.55$

Unapređivački heuristički postupci



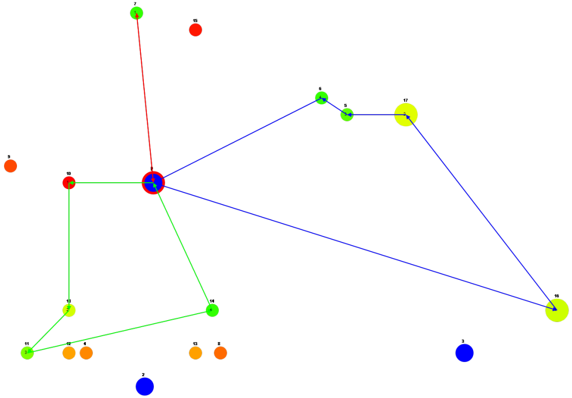
Slika: *E-VRPTW LNS ruin*, $D = 285.11$

unapređivački heuristički postupci



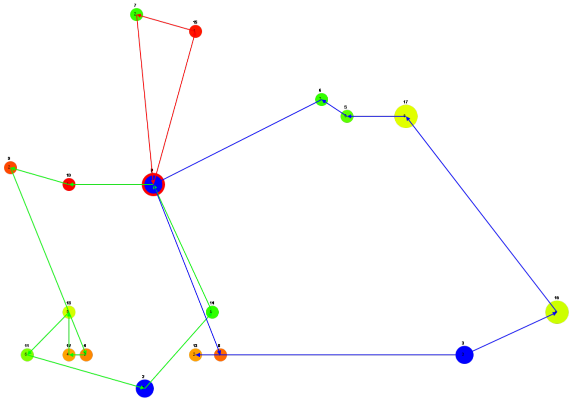
Slika: *E-VRPTW LNS recreate*, $D = 326.25$

unapređivački heuristički postupci



Slika: *E-VRPTW LNS ruin*, $D = 223.85$

Unapređivački heuristički postupci



Slika: *E-VRPTW LNS recreate*, $D = 275.13$

Susjedno orijentirani metaheuristički postupci

- Iterativno pretražuju susjedstvo trenutnog rješenja
  - Simulirano kaljenje, [59, 20, 34, 23, 33, 37]
  - Tabu pretraživanje, [60, 20, 26, 31]
  - (Adaptivno) varijabilno pretraživanje susjedstva, [20, 28, 37, 10]
  - (Adaptivno) pretraživanje velikog susjedstva, [61, 33, 51, 24, 29, 23, 22, 38, 10]
  - Iterativna lokalna pretraga, [32, 35, 31]

Populacijski metaheuristički postupci

- Temelje se na prirodnim evolucijskim algoritmima u kojima preživljavaju "najsposobniji"
- Skup rješenja evoluira na način da se nova rješenja dobivaju kombinacijom već postojećih rješenja u skupu
  - Genetski algoritam, [62, 44, 63]
  - Algoritam mravlje kolonije, [64, 63]

Zaključak

- Specifične karakteristike rutiranja električne flote vozila
- Modeliranje stvarnih karakteristika:
  - miješana flota vozila, parcijalno i nelinearno punjenje, različite tehnologije punjenja, postavljanje stanica za punjenje, ograničenje kapaciteta stanice za punjenje itd.
- Model energetske potrošnje električnih vozila $\rightarrow$ matrica energetske potrošnje
- Buduća istraživanja
  - Dinamičko stanje prometne mreže $\rightarrow$ TD-E-VRP, [44]
  - Postupci rješavanja
    - Mali broj populacijskih algoritama
    - Poboljšanje susjedno orijentiranih metaheuristika $\rightarrow$ *ruin-recreate*, [58]
  - Hibridna električna vozila

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