MASTER THESIS No. 3010
DEFENSE PRESENTATION

A Heuristic Algorithm for Scheduling Aerial Resources for the Extinction of Large-scale Wildfires

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Mentor: prof. Lea Skorin-Kapov
Co-mentor: assoc. prof. Nina Skorin-Kapov

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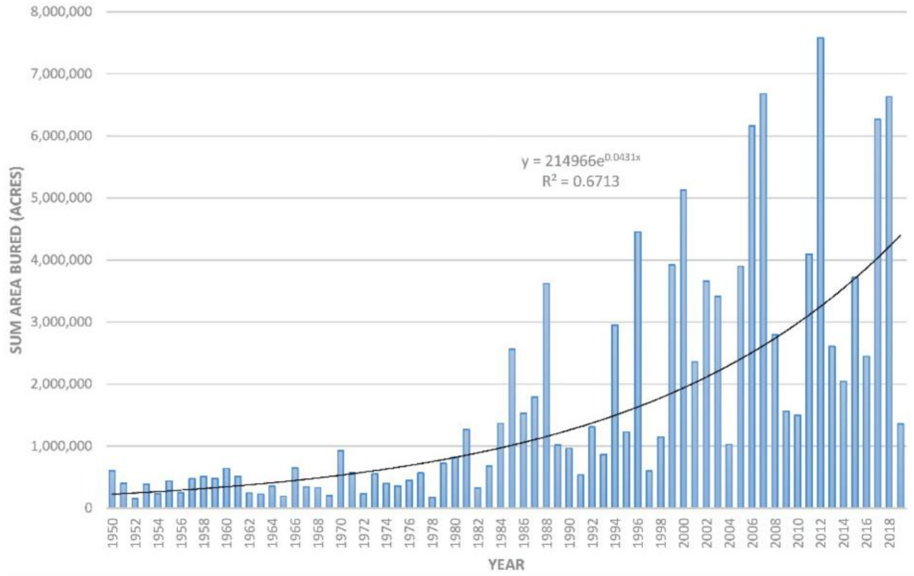
Motivation

- Increase in the annual total area burned
- Wildfire near Málaga, Spain
  - September 2021
  - $80\ \mathrm{km}^2$ burned
  - 51 aerial resources active in one day
- Scalable scheduling algorithms are required
  - Integer linear programming (ILP) models
    - Too slow, but can find optimal solutions
  - Model designed by prof. Nina Skorin-Kapov



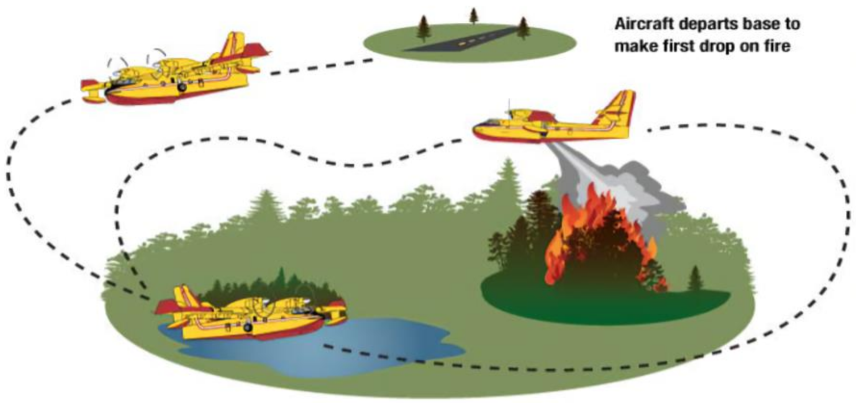
The annual total area burned in the western United States between 1950 and 2019 [1]

The Problem

- Discrete time – 45 slots of 20-minute intervals
- Multiple fire fronts
- Helicopters and airplanes
  - Capacity, availability, drops per hour, rest time, etc.
- Attempt to meet the target water content

- Large-scale wildfires
  - More than 20 resources
  - Lasting several days
- Obey Spanish regulation of civil aviation

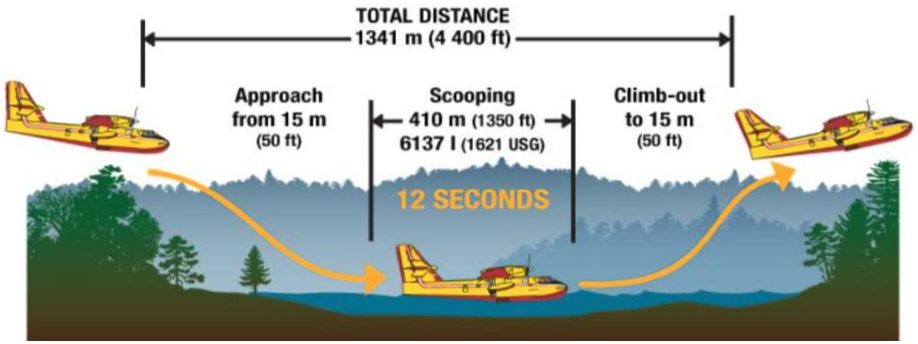
- Output:
  - Flight schedule for one day
  - Set of takeoffs: $\{(k_1, f_1, t_1), \ldots\}$
  - $\sim 10^{200}$ valid solutions



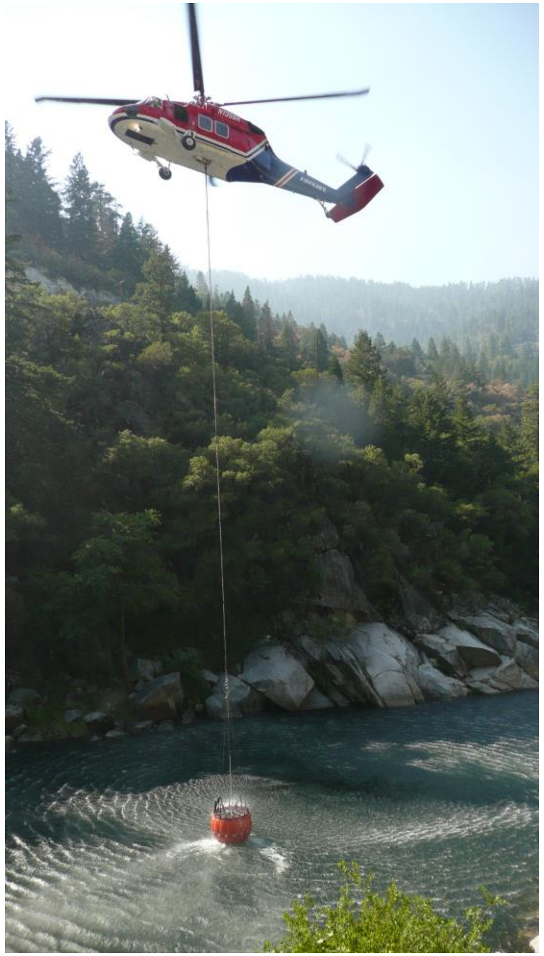
A flight path which includes takeoff and repeated filling and dropping of water [2]

Constraint Examples

- Helicopters and airplanes cannot fly at the same front at the same time
  - Different flight paths
- Airplanes cannot be assigned to some fronts
  - Inaccessible water refilling points



An illustration of water scooping by an amphibious aircraft [2]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Objectives

1. Maximize the total negative water surplus – $WS_n \geq 0$
2. Maximize the minimal water surplus – $Z \in \mathbb{R}$
3. Maximize the total water output – $WO \geq 0$

$$\begin{array}{ccccc} \text{Targets} & & \text{Dropped} & & \text{Surplus} \\ \begin{bmatrix} -4 & -2 \\ -3 & -2 \\ -3 & -1 \end{bmatrix} & + & \begin{bmatrix} 5 & 0 \\ 5 & 2 \\ 0 & 2 \end{bmatrix} & = & \begin{bmatrix} 1 & -2 \\ 2 & 0 \\ -3 & 1 \end{bmatrix} \end{array}$$

$WO = 14$ $\quad Z = -3$

$WS_n = -5$

- $\max(a_1 \cdot WS_n + a_2 \cdot Z + a_3 \cdot WO)$

- A continuous flow of water is desired
- Cost is not optimized
  - Handled during the resource allocation phase

Heuristic Algorithm

- GRASP
  - Randomized greedy algorithm
    - Restricted candidate list (RCL)
  - Local search
    - Large neighborhood search
      - Implicit neighborhood via *destroy* and *repair* methods (DFS)
    - Simulated annealing
      - Accept non-improving neighbors

Implementation

- CLI application written in C++20
- Thread pool
  - Each GRASP iteration is a task
- Focused on performance
  - Polynomial time complexity
    - $\mathcal{O}\big((L+K)\cdot(KFT)^2\big)$
  - Avoided copying the schedule
    - ~5x performance increase
  - Cached constraint violations

Test Scenarios

- 420 instances divided into 84 scenarios
  - Seven scenario sizes
  - Four distributions of the target water content over time and fronts
- Average-sized drop of water is ~ 3000 L
- Up to ~ 1000 drops and ~ 110 flights

Scenario	Aircraft	Fronts
K07_F02	7	2
K10_F03	10	3
K15_F03	15	3
K20_F04	20	4
K25_F04	25	4
K30_F05	30	5
K35_F05	35	5

Aircraft subtype	Capacity (C_k)	Avg. drops
Light helicopter	900 L	5
Medium helicopter	1500 L	5
Heavy helicopter	4500 L	4
Military helicopter	2100 L	5
Airplane	5500 L	3

Results (1/2)

- ILP executed for 2h on 8 threads

- 240 instances with $K \geq 20$
  - Heuristic outperformed ILP in all of them
- 60 instances with $K = 15$
  - Heuristic outperformed ILP in 50 instances ($\sim 83\%$)
- 120 instances with $K \leq 10$
  - ILP found 80 optimal solutions
  - Heuristic found 61 optimal solutions ($\sim 75\%$)

		NUOF + IA			NUOF + MUOT			UOF + IA			UOF + MUOT			
		H	ILP	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	
K07_F02	WS_n	-2989^{*}	$\mathbf{-2883}^{**}$	−0.035	-2012^{*}	$\mathbf{-1844}^{**}$	−0.056	-2301^{*}	$\mathbf{-2274}^{**}$	−0.009	$\mathbf{-1823}^{**}$	-1823^{**}	0.000	WS_n
	Z	-1019^{*}	$\mathbf{-973}^{**}$	−0.015	-763^{*}	$\mathbf{-881}^{**}$	0.039	-1318^{*}	$\mathbf{-1318}^{**}$	0.000	$\mathbf{-1015}^{**}$	-1015^{**}	0.000	Z
	WO	449896^{*}	$\mathbf{442592}^{**}$	2.435	493192^{*}	$\mathbf{487790}^{**}$	1.801	442313^{*}	$\mathbf{438901}^{**}$	1.137	$\mathbf{491523}^{**}$	491225^{**}	0.099	WO
K10_F03	WS_n	$\mathbf{-896}^{*}$	-1127^{*}	0.082	**−2854**	-2948^{*}	0.033	**−1542**	-2207^{*}	0.236	**−4599**	−6554	0.694	WS_n
	Z	$\mathbf{-444}^{*}$	-536^{*}	0.033	**−1205**	-1225^{*}	0.007	**−546**	-777^{*}	0.082	**−1698**	−1927	0.082	Z
	WO	$\mathbf{720051}^{*}$	716686^{*}	1.195	**652713**	654070^{*}	−0.482	**710147**	707986^{*}	0.767	**641558**	635346	2.205	WO
K15_F03	WS_n	**−2542**	-2973^{*}	0.152	**−2721**	−4002	0.453	**−3527**	−4486	0.339	**−3573**	−5769	0.777	WS_n
	Z	**−1296**	-1444^{*}	0.052	**−1271**	−1745	0.168	**−1446**	−1606	0.057	**−1232**	−1821	0.208	Z
	WO	**980092**	975986^{*}	1.452	**914063**	897083	6.004	**977230**	968173	3.203	**900147**	910705	−3.734	WO
K20_F04	WS_n	**−1715**	−10184	3.145	**−1470**	−9855	3.114	**−1466**	−7625	2.287	**−1708**	−13600	4.416	WS_n
	Z	**−777**	−2880	0.781	**−588**	−2921	0.866	**−353**	−2185	0.680	**−790**	−1988	0.445	Z
	WO	**1210731**	1135203	28.049	**1251442**	1237540	5.163	**1246658**	1205878	15.144	**1239359**	1197545	15.528	WO
K25_F04	WS_n	**−152**	−13990	5.104	**−88**	−18996	6.973	**−656**	−37551	13.607	**−63**	−13246	4.862	WS_n
	Z	**−55**	−3156	1.144	**86**	−3476	1.314	**−120**	−4562	1.639	**190**	−2907	1.142	Z
	WO	**1611245**	1606310	1.820	**1605835**	1515948	33.150	**1666759**	1472142	71.774	**1629678**	1546952	30.509	WO
K30_F05	WS_n	**−470**	−89250	32.474	**−284**	−26813	9.704	**−625**	−62326	22.569	**−595**	−61670	22.340	WS_n
	Z	**−24**	−6762	2.465	**−106**	−4317	1.541	**−365**	−5088	1.728	**−159**	−4129	1.452	Z
	WO	**1937631**	1689280	90.842	**1927256**	1767732	58.351	**1971345**	1655500	115.530	**2044985**	1749104	108.228	WO
K35_F05	WS_n	**−968**	−134787	48.814	**−175**	−124334	45.291	**−696**	−142156	51.602	**−365**	−132965	48.370	WS_n
	Z	**−561**	−8363	2.846	**57**	−6597	2.427	**−273**	−5479	1.899	**−158**	−4322	1.519	Z
	WO	**2121506**	1819684	110.099	**2148979**	1785340	132.648	**2252157**	1659594	216.155	**2162483**	1690788	172.065	WO
		H	ILP	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	

MUOT		UOF + IA			UOF + MUOT			
P	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	
4**	−0.056	−2301*	**−2274****	−0.009	**−1823****	−1823**	0.000	WS_n
1**	0.039	−1318*	**−1318****	0.000	**−1015****	−1015**	0.000	Z
0**	1.801	442313*	**438901****	1.137	**491523****	491225**	0.099	WO
8*	0.033	**−1542**	−2207*	0.236	**−4599**	−6554	0.694	WS_n
5*	0.007	**−546**	−777*	0.082	**−1698**	−1927	0.082	Z
0*	−0.482	**710147**	707986*	0.767	**641558**	635346	2.205	WO
2	0.453	**−3527**	−4486	0.339	**−3573**	−5769	0.777	WS_n
5	0.168	**−1446**	−1606	0.057	**−1232**	−1821	0.208	Z
3	6.004	**977230**	968173	3.203	**900147**	910705	−3.734	WO
5	3.114	**−1466**	−7625	2.287	**−1708**	−13600	4.416	WS_n
1	0.866	**−353**	−2185	0.680	**−790**	−1988	0.445	Z
0	5.163	**1246658**	1205878	15.144	**1239359**	1197545	15.528	WO

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Z
3	6.004	**977230**	968173	3.203	**900147**	910705	−3.734	WO
5	3.114	**−1466**	−7625	2.287	**−1708**	−13600	4.416	WS_n
1	0.866	**−353**	−2185	0.680	**−790**	−1988	0.445	Z
0	5.163	**1246658**	1205878	15.144	**1239359**	1197545	15.528	WO
6	6.973	**−656**	−37551	13.607	**−63**	−13246	4.862	WS_n
6	1.314	**−120**	−4562	1.639	**190**	−2907	1.142	Z
8	33.150	**1666759**	1472142	71.774	**1629678**	1546952	30.509	WO
3	9.704	**−625**	−62326	22.569	**−595**	−61670	22.340	WS_n
7	1.541	**−365**	−5088	1.728	**−159**	−4129	1.452	Z
2	58.351	**1971345**	1655500	115.530	**2044985**	1749104	108.228	WO
4	45.291	**−696**	−142156	51.602	**−365**	−132965	48.370	WS_n
7	2.427	**−273**	−5479	1.899	**−158**	−4322	1.519	Z
0	132.648	**2252157**	1659594	216.155	**2162483**	1690788	172.065	WO
P	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	

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	Z	-1019^{*}	**-973^{**}**	−0.015	-763^{*}	**-881^{**}**	0.039	-1318^{*}	**-1318^{**}**	0.000	**-1015^{**}**	-1015^{**}	0.000	Z
	WO	449896^{*}	**442592^{**}**	2.435	493192^{*}	**487790^{**}**	1.801	442313^{*}	**438901^{**}**	1.137	**491523^{**}**	491225^{**}	0.099	WO
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	Z	**−1296**	-1444^{*}	0.052	**−1271**	−1745	0.168	**−1446**	−1606	0.057	**−1232**	−1821	0.208	Z
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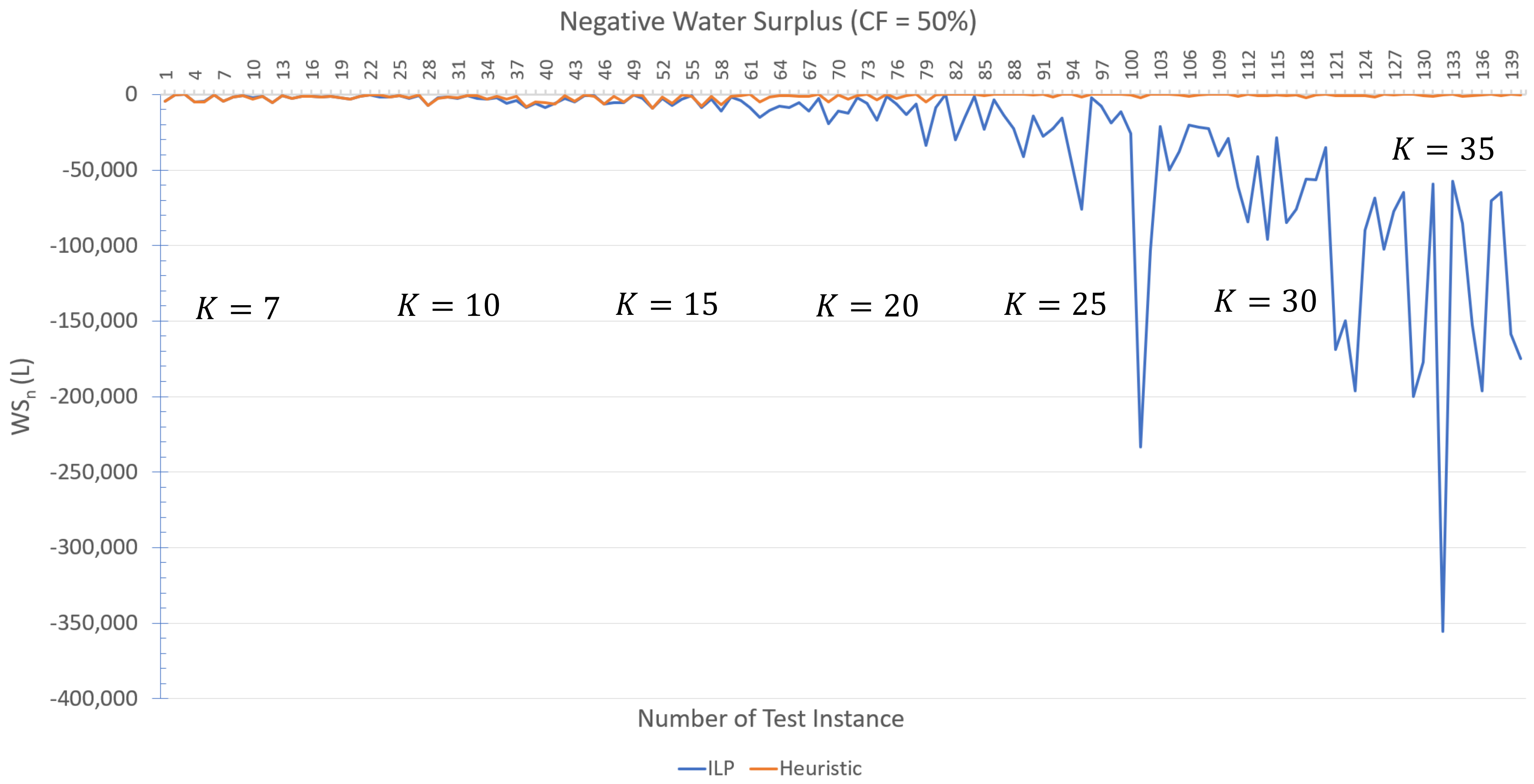
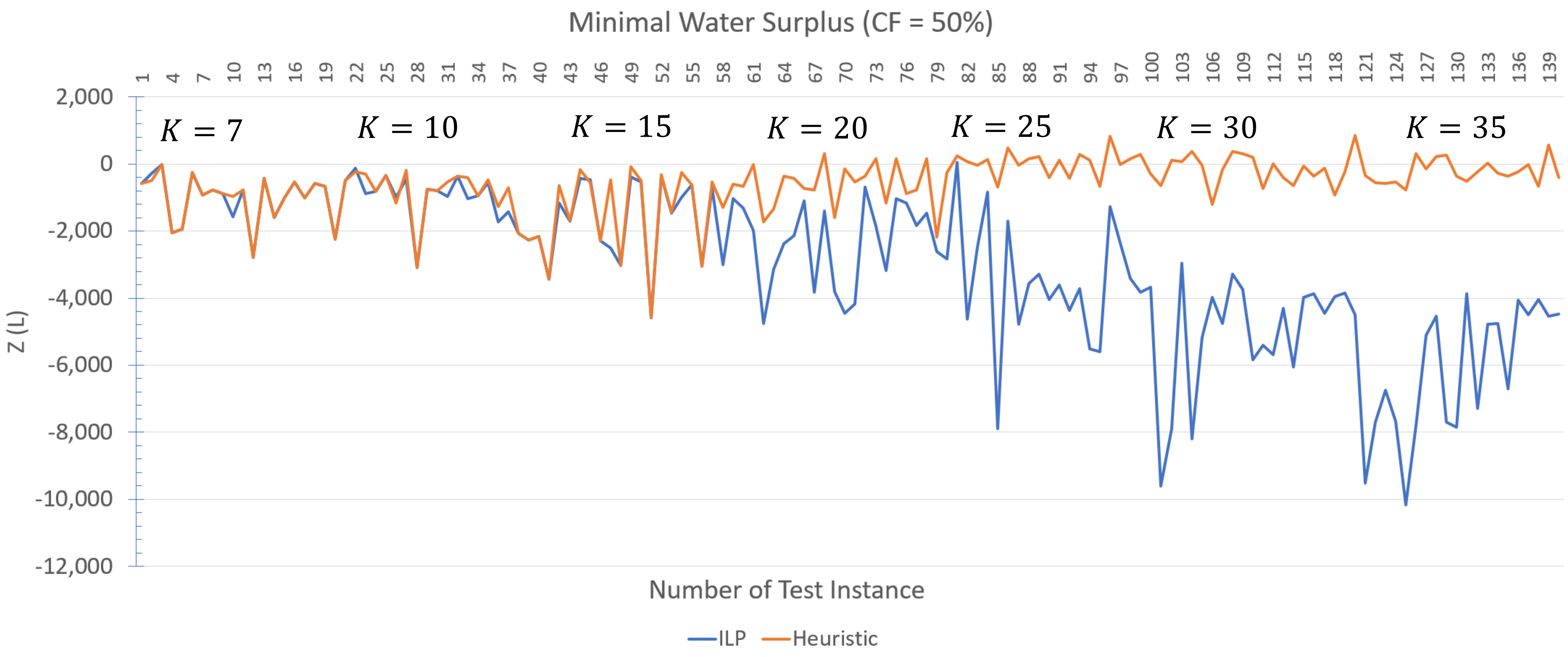
	WO	**2121506**	1819684	110.099	**2148979**	1785340	132.648	**2252157**	1659594	216.155	**2162483**	1690788	172.065	WO
		H	ILP	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	H	ILP	Deviation (no. of dls.)	

Results (2/2)

- Linear solver executed for 6h on 16 threads
  - Effectively 6x longer execution
- Execution was not extended for the heuristic algorithm

		$CF = 50\%$		
		H	ILP	Deviation (no. of dls.)
K15_F03	WS_n	**−1357**	−1653	0.10
	Z	**−545**	−545	0.00
	WO	**833730**	830704	1.07
K20_F04	WS_n	**−978**	−4868	1.44
	Z	**−433**	−2174	0.65
	WO	**1133633**	1142120	−3.15
K25_F04	WS_n	**0**	−124	0.05
	Z	**161**	−124	0.11
	WO	**1427212**	1507580	−29.64
K30_F05	WS_n	**0**	−37635	13.77
	Z	**12**	−4960	1.82
	WO	**2162213**	2041240	44.25
K35_F05	WS_n	**−378**	−16843	6.01
	Z	**−244**	−4000	1.37
	WO	**2031193**	1888430	52.08


Negative Water Surplus (CF = 50%)
WS_n (L)
0
-50,000
-100,000
-150,000
-200,000
-250,000
-300,000
-350,000
-400,000
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58 61 64 67 70 73 76 79 82 85 88 91 94 97 100 103 106 109 112 115 118 121 124 127 130 133 136 139
$K = 7$
$K = 10$
$K = 15$
$K = 20$
$K = 25$
$K = 30$
$K = 35$
Number of Test Instance
ILP
Heuristic



Minimal Water Surplus (CF = 50%)
2,000
0
-2,000
-4,000
-6,000
-8,000
-10,000
-12,000
Z (L)
1
4
7
10
13
16
19
22
25
28
31
34
37
40
43
46
49
52
55
58
61
64
67
70
73
76
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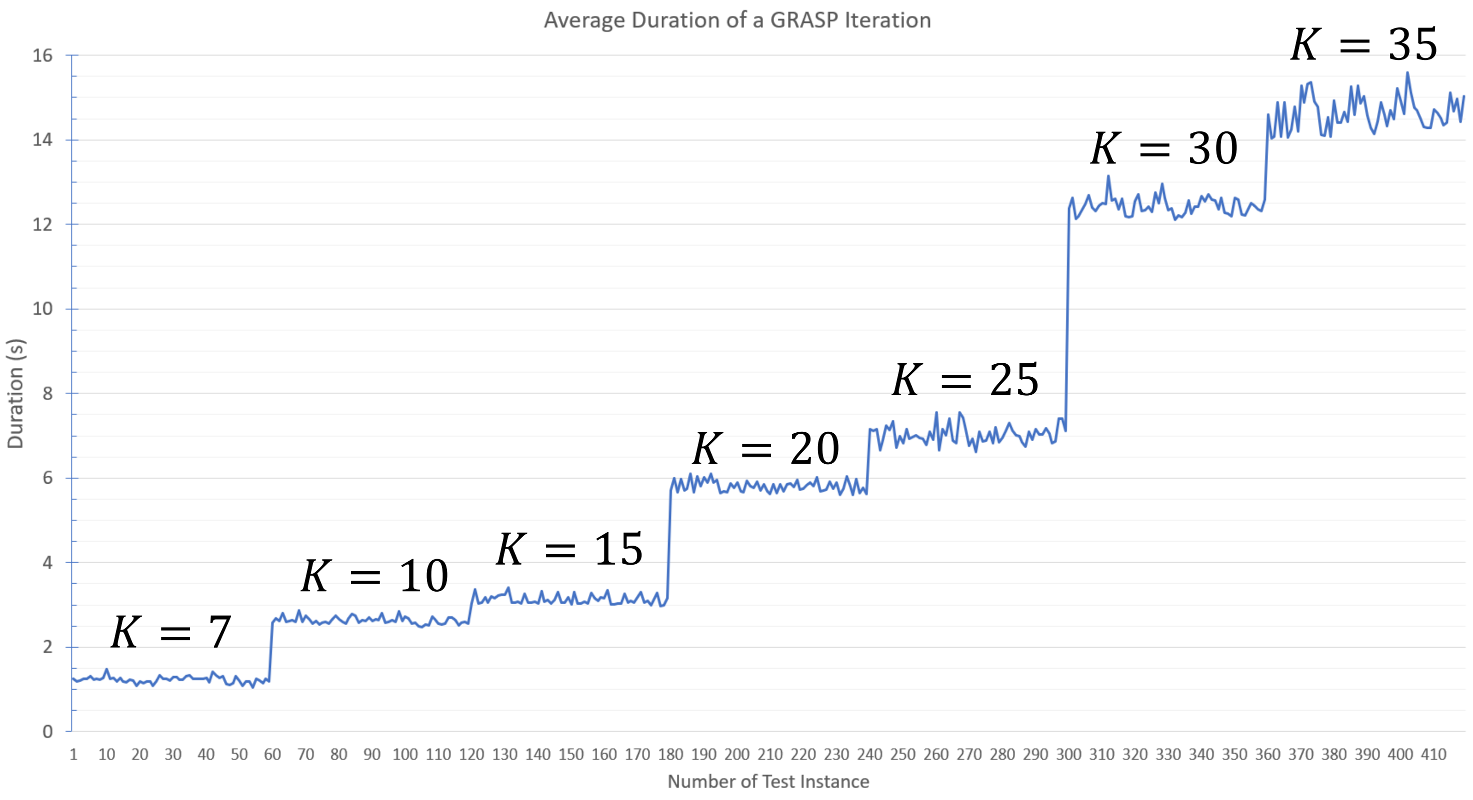
82
85
88
91
94
97
100
103
106
109
112
115
118
121
124
127
130
133
136
139
$K = 7$
$K = 10$
$K = 15$
$K = 20$
$K = 25$
$K = 30$
$K = 35$
Number of Test Instance
ILP
Heuristic

Execution time

- Runs in under 5 minutes
- Uses under 10 MB of RAM
- Executable has 440 KB



Next Steps

Publish an article

Co-authored with prof. Nina Skorin-Kapov

Present the results

Spanish Ministry of Development (MITMA)

References

[1] K. T. Weber and R. Yadav, "Spatiotemporal Trends in Wildfires across the Western United States (1950-2019)," *Remote Sensing*, vol. 12, no. 18, 2020.

[2] Viking Air, "Viking's Aerial Firefighter – Firefighting Technique." https://aerialfirefighter.vikingair.com/firefighting/firefighting-technique. Accessed on: 2022-06-18.

Thank you!

github.com/LMesaric/MSc-Thesis-FER-2022