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Applications of Constraint Programming

Insight

SFI RESEARCH CENTRE FOR DATA ANALYTICS

Helmut Simonis

CRT-AI CP Week 2024

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FUNDED BY:

European Union European Regional Development Fund

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Acknowledgments

This publication has emanated from research conducted with the financial support of Science Foundation Ireland under Grant number 12/RC/2289-P2 at Insight the SFI Research Centre for Data Analytics at UCC, which is co-funded under the European Regional Development Fund.
A version of this material was developed as part of the ECLiPSe ELearning course: `https://eclipseclp.org/ELearning/index.html`. Support from Cisco Systems and the Silicon Valley Community Foundation is gratefully acknowledged.

Applications are important

- Provide motivation for basic research
  - Which constraints, methods are needed
- Provide realistic benchmark problems
  - Easy to optimize for pointless results
- Shows that research has potential benefits
  - Much easier to convince funding agencies
- Typically much easier to explain than solver internals
  - Interest students, do outreach

Main Application Areas for CP

- Scheduling
  - By far the largest application area
- Product Configuration
  - No longer much of a research focus
  - Start with Ulrich Junker's chapter in Handbook of Constraint Programming
- Rostering and Assignment
  - Propagation is very powerful
  - Start with Demirović, E., Stuckey, P.J. (2018). Constraint Programming for High School Timetabling: A Scheduling-Based Model with Hot Starts. CPAIOR 2018.
- Software/Hardware Design and Testing
  - Sometimes using specialized domains (uint32)
  - Start with Arnaud Gotlieb video

    `https://www.youtube.com/watch?v=E1Seayx3eXU`
- Transportation
  - Hybrids with other techniques
  - Start with Augustin Delecluse, Pierre Schaus, and Pascal Van Hentenryck. Sequence Variables for Routing Problems. CP 2022.

Outline

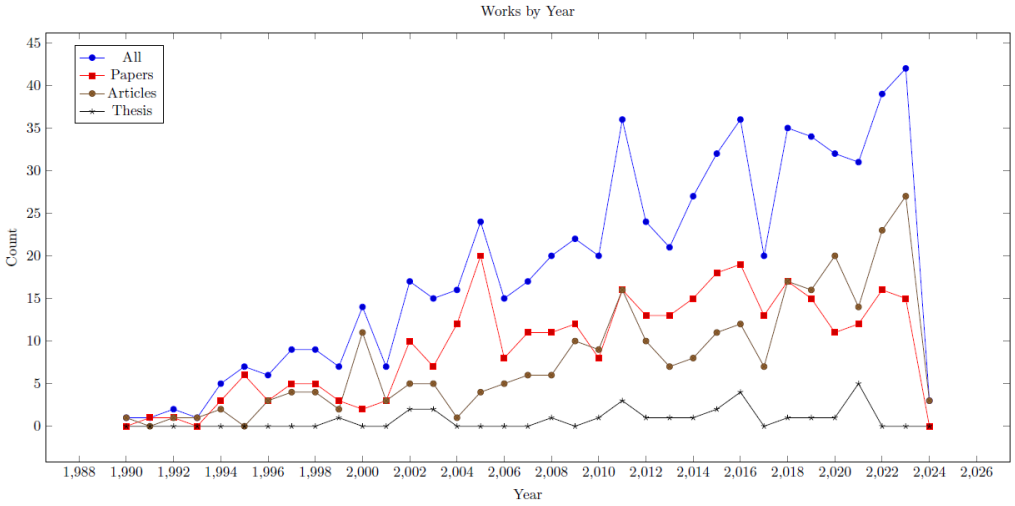
A Survey of the Existing Literature

- Joint work with Cemalettin Ozt urk, MTU
- What is out there
- Where to start
- Where to publish
- I’m interested in some specific topic, what is relevant

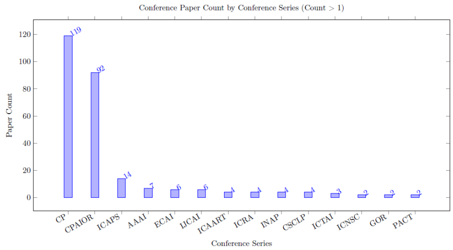
Methodology

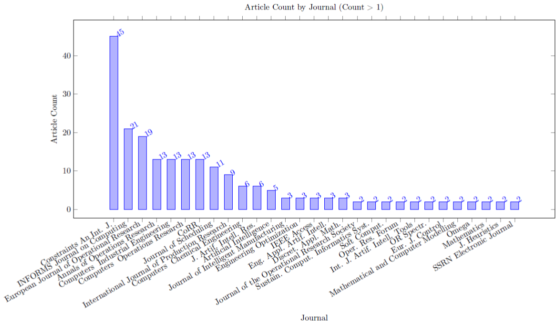
- Manually curated list of works, somewhat inclusive
- Starting with bibtex files
- Citation links through OpenCitations (open access)
- Content analysis on local copies of pdf files
- Closure of domain by analyzing missing cited and citing works
- Limited manual analysis of works (datasets, code)
- Results presented as LaTeX documents
- Open source analysis on git: `https://hsimonis.github.io/pthg24/`

Overall Analysis (Based on 671 Works)



Origin of Papers/Articles





Most Recent Articles

Table 5: Works from bibtex (Total 274)

Key	Authors	Title	LC	Cite	Year	Conference /Journal	Pages	Nr Cites	Nr Refs	b	c
ForbesHJST24 ForbesHJST24	M. Forbes, M. Harris, H. Jansen, F.A. van der Schoot, T. Taimre	Combining optimisation and simulation using logic-based Benders decomposition	Yes	[217]	2024	European Journal of Operational Research	15	0	26	1314	1496
PrataAN23 PrataAN23	Bruno A. Prata, Levi R. Abreu, Marcelo S. Nagano	Applications of constraint programming in production scheduling problems: A descriptive bibliometric analysis	Yes	[509]	2024	Results in Control and Optimization	17	0	0	1427	1497
abs-2402-00459 abs-2402-00459	S. Nguyen, Dhananjay R. Thiruvady, Y. Sun, M. Zhang	Genetic-based Constraint Programming for Resource Constrained Job Scheduling	Yes	[469]	2024	CoRR	21	0	0	1495	1498
AbreuNP23 AbreuNP23	Levi Ribeiro de Abreu, Marcelo Seido Nagano, Bruno A. Prata	A new two-stage constraint programming approach for open shop scheduling problem with machine blocking	Yes	[168]	2023	International Journal of Production Research	20	1	47	1243	1499
AbreuPNF23 AbreuPNF23	Levi R. Abreu, Bruno A. Prata, Marcelo S. Nagano, Jose M. Framinan	A constraint programming-based iterated greedy algorithm for the open shop with sequence-dependent processing times and makespan minimization	Yes	[3]	2023	Computers Operations Research	12	0	46	1244	1500
Adelgren2023 Adelgren2023	N. Adelgren, Christos T. Maravelias	On the utility of production scheduling formulations including record keeping variables	Yes	[7]	2023	Computers Industrial Engineering	12	0	43	1245	1501
AfsarVPG23 AfsarVPG23	S. Afsar, Camino R. Vela, Juan José Palacios, I. González-Rodríguez	Mathematical models and benchmarking for the fuzzy job shop scheduling problem	Yes	[8]	2023	Computers Industrial Engineering	14	0	50	1246	1502
AkramNHRSA23 AkramNHRSA23	Bilal Omar Akram, Nor Kamariah Noordin, F. Hashim, Mohd Fadlee A. Rasid, Mustafa Ismael Salman, Abdulrahman M. Abdulghani	Joint Scheduling and Routing Optimization for Deterministic Hybrid Traffic in Time-Sensitive Networks Using Constraint Programming	Yes	[13]	2023	IEEE Access	16	0	0	1248	1503
AlfieriGPS23 AlfieriGPS23	A. Alfieri, M. Garraffa, E. Pastor, F. Salassa	Permutation flowshop problems minimizing core waiting time and core idle time	Yes	[15]	2023	Computers Industrial Engineering	13	0	37	1249	1504
Caballero23 Caballero23	Jordi Coll Caballero	Scheduling through logic-based tools	Yes	[127]	2023	Constraints An Int. J.	1	0	0	1287	1505
CzerniachowskaWZ23 CzerniachowskaWZ23	K. Czerniachowska, R. Wichniarek, K. Żywicki	Constraint Programming for Flexible Flow Shop Scheduling Problem with Repeated Jobs and Repeated Operations	Yes	[159]	2023	Advances in Science and Technology Research Journal	14	0	0	1297	1506
FahimiQ23 FahimiQ23	H. Fahimi, C. Quimper	Overload-Checking and Edge-Finding for Robust Cumulative Scheduling	No	[207]	2023	INFORMS Journal on Computing	null	0	16	No	1507
Fatemi-AnarakiTFV23 Fatemi-AnarakiTFV23	S. Fatemi-Anaraki, R. Tavakkoli-Moghaddam, M. Foumani, B. Vahedi-Nouri	Scheduling of Multi-Robot Job Shop Systems in Dynamic Environments: Mixed-Integer Linear Programming and Constraint Programming Approaches	Yes	[212]	2023	Omega	15	7	60	1312	1508
GhasemiMH23 GhasemiMH23	S. Ghasemi, R. Tavakkoli-Moghaddam, M. Hamid	Operating room scheduling by emphasising human factors and dynamic decision-making styles: a constraint programming method	No	[242]	2023	International Journal of Systems Science: Operations Logistics	null	0	104	No	1509
GuoZ23 GuoZ23	P. Guo, J. Zhu	Capacity reservation for humanitarian relief: A logic-based Benders decomposition method with subgradient cut	Yes	[269]	2023	European Journal of Operational Research	29	0	112	1325	1510
GurPAE23 GurPAE23	S. Gür, M. Pinarbasi, Haci Mehmet Alakas, T. Eren	Operating room scheduling with surgical team: a new approach with constraint programming and goal programming	Yes	[270]	2023	Central Eur. J. Oper. Res.	25	1	40	1327	1511
IsikYA23 IsikYA23	Eyüp Ensar Isik, Seyda Topaloglu Yildiz, Özge Satir Akpunar	Constraint programming models for the hybrid flow shop scheduling problem and its extensions	Yes	[321]	2023	Soft Comput.	28	0	127	1350	1512
JuvinHL23a JuvinHL23a	C. Juvin, L. Houssin, P. Lopez	Logic-based Benders decomposition for the preemptive flexible job-shop scheduling problem	Yes	[331]	2023	Computers Operations Research	17	0	40	1355	1513
LacknerMMWW23 LacknerMMWW23	M. Lackner, C. Mrkvicka, N. Musliu, D. Walkiewicz, F. Winter	Exact methods for the Oven Scheduling Problem	Yes	[374]	2023	Constraints An Int. J.	42	0	32	1371	1514

Automatically Extracted Article Features

Table 6: Automatically Extracted ARTICLE Properties (Requires Local Copy)

Work	Pages	Concepts	Classification	Constraints	Prog Languages	CP Systems	Areas	Industries	Benchmarks	Algorithm	a	c
Laborie03 [369]	38	task, precedence, order, cmax, machine, job, activity, re-scheduling, setup-time, release-date, inventory, preempt, job-shop, resource, scheduling, make-span		cycle, table constraint, cumulative, disjunctive	C++	Ilog Scheduler			benchmark	edge-finding, not-last, energetic reasoning, not-first, time-tabling	1201	1731
LaborieRSV18 [372]	41	release-date, job-shop, resource, activity, precedence, sequence dependent setup, earliness, scheduling, machine, inventory, transportation, manpower, due-date, setup-time, batch process, order, tardiness, flow-shop, job, make-span, re-scheduling, task, distributed	psplib, parallel machine, RCPSP	alternative constraint, cumulative, noOverlap, disjunctive, span constraint, cycle, alwaysIn, endBeforeStart	C , Python, C++, Java	CHIP, Gecode, Ilog Solver, Cplex, Ilog Scheduler, OPL, Choco Solver, CPO	semiconductor, railway, container terminal, satellite, robot, pipeline, aircraft, shipping line	chemical industry, petrochemical industry	real-world, CSPlib, benchmark	edge-finding	1080	1610
LacknerMMWW23 [374]	42	release-date, batch process, setup-time, job, order, due-date, tardiness, scheduling, make-span, machine, task, lateness, job-shop, earliness	parallel machine, OSP, single machine	alternative constraint, disjunctive, bin-packing, noOverlap, cumulative, endBeforeStart		Chuffed, Cplex, OPL, CPO, OR-Tools, MiniZinc, Gurobi	semiconductor, oven scheduling	electronics industry, steel industry, manufacturing industry	random instance, industrial partner, benchmark, instance generator, zenodo, real-life	time-tabling	984	1514
LammaMM97 [377]	15	job-shop, resource, scheduling, precedence, order, task, job, distributed, no-wait		circuit, disjunctive	C++, Prolog	ECLiPSe, OPL, CHIP	railway		real-life		1230	1760
LetortCB15 [385]	52	machine, make-span, job, precedence, resource, scheduling, task, order	psplib	cumulative, cycle, bin-packing	Java, Prolog	Choco Solver, CHIP, SICStus			generated instance, Roadef, benchmark, random instance	energetic reasoning, sweep, edge-finding	1110	1640
LiW08 [386]	18	precedence, activity, resource, completion-time, setup-time, make-span, scheduling, machine, preempt, job-shop, no preempt, job, re-scheduling, open-shop, due-date, task, order	RCPSP	disjunctive, cycle, bin-packing		Ilog Solver, OZ, Cplex, ECLiPSe, OPL, CHIP			real-world		1178	1708
LiessM08 [388]	12	preempt, resource, scheduling, machine, job, activity, precedence, job-shop, task, make-span, order, cmax	RCPSP, psplib	disjunctive, cumulative	C++	OZ			benchmark	edge-finding	1179	1709
LimtanyakulS12 [393]	32	release-date, scheduling, order, completion-time, job, resource, activity, tardiness, machine, due-date, precedence		table constraint, disjunctive, bin-packing, cumulative		OZ, Ilog Scheduler, Cplex	robot, automotive	automotive industry	random instance, real-life, generated instance, industrial partner, benchmark	not-last, energetic reasoning, not-first, edge-finding	1133	1663
LombardiM10a [402]	30	due-date, distributed, order, job, make-span, release-date, re-scheduling, task, completion-time, resource,	TCSP	cycle, span constraint, cumulative, disjunctive, table	C	Cplex			real-world, benchmark, real-life	sweep	1160	1690

Manually Extracted Article Features

Table 4: Manually Defined PAPER Properties

Key	Title (Local Copy)	CP System	Bench	Links	Data Avail	Sol Avail	Code Avail	Related To	Classification	Constraints	a	b
AalianPG23 AalianPG23 [1]	Optimization of Short-Term Underground Mine Planning Using Constraint Programming	CP Opt	real-world	1	n		n			?	1	325
Bit-Monnot23 Bit-Monnot23 [96]	Enhancing Hybrid CP-SAT Search for Disjunctive Scheduling	ARIES CP Opt OR-Tools Mistral	real-world, github, benchmark	1	y		y	-	JSSP OSSP	-	2	371
EfthymiouY23 EfthymiouY23 [194]	Predicting the Optimal Period for Cyclic Hoist Scheduling Problems	OR-Tools	benchmark, random instance, generated instance, real-life, industrial instance	3	n		n	-	CHSP	-	3	415
JuvinHHL23 JuvinHHL23 [328]	An Efficient Constraint Programming Approach to Preemptive Job Shop Scheduling	CP Opt Mistral	supplementary material, github, benchmark	6	ref		y		PJSSP	endBeforeStart span noOverlap	4	476
JuvinHL23 JuvinHL23 [330]	Constraint Programming for the Robust Two-Machine Flow-Shop Scheduling Problem with Budgeted Uncertainty	CP Opt Cplex	real-world	0	ref		n	-	Perm FSSP	endBeforeStart noOverlap sameSequence	5	477
KameugneFND23 KameugneFND23 [336]	Horizontally Elastic Edge Finder Rule for Cumulative Constraint Based on Slack and Density	?	benchmark	5	BL PSPlib		n	-	RCPSPs	cumulative	6	480
KimCMLLP23 KimCMLLP23 [345]	Iterated Greedy Constraint Programming for Scheduling Steelmaking Continuous Casting	Gurobi OR-Tools	real-world, benchmark, zenodo	0	y		n	-	SCC	alternative noOverlap	7	485
Mehdizadeh-Somarin23 Mehdizadeh-Somarin23 [430]	A Constraint Programming Model for a Reconfigurable Job Shop Scheduling Problem with Machine Availability	CP Opt	random instance	0	n		n	-	JSSP RMS	alternative endBeforeStart noOverlap	8	529
PerezGSL23 PerezGSL23 [496]	A Constraint Programming Model for Scheduling the Unloading of Trains in Ports	custom	real-world, generated instance	0	n		n	-	SUTP	table disjunctive	9	553
PovedaAA23 PovedaAA23 [506]	Partially Preemptive Multi Skill/Mode Resource-Constrained Project Scheduling with Generalized Precedence Relations and Calendars	CP Opt MiniZinc Chuffed	real-world, github, benchmark, industrial instance, real-life	4	y		y		PP-MS-MMRCPSP/max-cal		10	557
SquillaciPR23 SquillaciPR23 [564]	Scheduling Complex Observation Requests for a Constellation of Satellites: Large Neighborhood Search Approaches	Cplex Studio	github, benchmark	2	y		n	-	EOSP	?	11	584
TardivoDFMP23 TardivoDFMP23 [575]	Constraint Propigation on GPU: A Case Study for the Cumulative Constraint	MiniCPP MiniZinc	bitbucket, github, benchmark, real-world	9	PSPLib BL Pack		y	-	RCPSP	cumulative	12	590
TasselGS23 TasselGS23 [576]	An End-to-End Reinforcement Learning Approach for Job-Shop Scheduling Problems Based on Constraint Programming	custom Choco	industrial instance, real-world, supplementary material, github, benchmark	0	ref		y	-	JSSP	noOverlap	13	591
WangB23 WangB23 [629]	Dynamic All-Different and Maximal Cliques Constraints for Fixed Job Scheduling	FaCiLe	established random instance	0	(y)		n	[628]	FJS	-	14	620
YuraszeckMC23	A competitive constraint programming approach	CP Opt	github, bench-	0	ref		n	-	GSSP	noOverlap	15	633

Extracted Features: Application Areas

Table 16: Works for Concepts of Type ApplicationAreas

Type	Keyword	High	Medium	Low
ApplicationAreas	COVID	GuoZ23 [269]	GeibingerKKMMW21 [234]	Fatemi-AnarakiTFV23 [212], Mehdizadeh-Somarin23 [430], GurPAE23 [270], JuvinHL23a [331], OujanaAYB22 [487], Lemos21 [381]
ApplicationAreas	HVAC	LimHTB16 [390], LimBTBB15 [391], GrimesIOS14 [260]		
ApplicationAreas	agriculture			AkramNHRSA23 [13], BenderWS21 [84], HamPK21 [275], Astrand21 [35], QinWSLS21 [511], Astrand0F21 [36], MejiaY20 [431]
ApplicationAreas	aircraft	PohlAK22 [502], WangB20 [628], TranDRFWOVB16 [596], Fahimi16 [205], BajestaniB13 [42], LombardiM12 [405], BajestaniB11 [41], FrankK05 [219], ArtiouchineB05 [34], Simonis99 [558]	WangB23 [629], GombolayWS18 [253], Ham18 [273], Simonis07 [559], SakkoutW00 [529], Simonis95a [556]	PrataAN23 [509], PovedaAA23 [506], Adelgren2023 [7], EtminaniesfahaniGNMS22 [202], ElciOH22 [195], ZarandiASC20 [654], HauderBRPA20 [283], abs-1902-09244 [282], Hooker19 [312], LaborieRSV18 [372], HookerH17 [314], TranAB16 [594], LombardiI10 [398], Laborie09 [370], KovacsB08 [355], KrogtLPHJ07 [608], MartinPY01 [427], SimonisCK00 [560], GruianK98 [264], Darby-DowmanLMZ97 [163], Wallace96 [625], Simonis95 [557], SimonisC95 [561]
ApplicationAreas	automotive		GuoZ23 [269], YuraszeckMPV22 [650], EmdeZD22 [199], Groleaz21 [261], LimtanyakulS12 [393], SunLYL10 [567], LombardiI10 [398], BarlattCG08 [52], SchlobW00 [532]	PovedaAA23 [506], NaderiRR23 [460], CzernlachowskaWZ23 [159], NaderiBZ22 [457], NaderiBZ22a [456], AntuoriHHEN21 [22], HubnerGSV21 [318], AbreuAPNM21 [166], KoehlerBFFHPSSS21 [348], VIkH121 [623], BarzeganiZP20 [61], GeibingerMM19 [236], abs-1911-04766 [235], BonfiettiZLM16 [113], Siala15a [552], SchnellH15 [533], AlesioNBG14 [181], HarjunkoskiMBC14 [279], BeniniBGM06 [88], KovacsV06 [360], Wallace96 [625]
ApplicationAreas	cable tree	KochlerBFFHPSSS21 [348]		
ApplicationAreas	car manufacturing		AntuoriHHEN21 [22]	BeldiceanuC94 [78]
ApplicationAreas	container terminal	QinDCS20 [512], SacramentoSP20 [526]	LaborieRSV18 [372]	abs-2312-13682 [497], PerezGSL23 [496], TouatBT22 [592], CauwelaertDS20 [142], WallaceY20 [627], ZarandiASC20 [654], FallahiAC20 [209], Hooker19 [312], CauwelaertDM816 [140], DajemeppeJ6 [172], DajemeppeCS15 [173], NovasH12 [476], CorreaLR07 [158], LimRX04 [389]
ApplicationAreas	crew-scheduling	ZarandiASC20 [654], PourDERB18 [505]	BourreauCGLT22 [118], Zahout21 [652], GombolayWS18 [253], Mason01 [429], Touraivane95 [595]	NaderiRR23 [460], WangB23 [629], Adelgren2023 [7], EtminaniesfahaniGNMS22 [202], NaderiBZ22a [456], NaderiBZ22 [457], HeinzNVH22 [295], ElciOH22 [195], Lemos21 [381], MokhtarzadehTNF20 [443], TangLWSK18 [574], HookerH17 [314], DoulabiRP16 [190], LipovetzkyBPS14 [394], HachemiGR11 [272], MilanoW09 [441], WuHB09 [643], MilanoW06 [440], BeldiceanuC02 [79], JainG01 [323], SimonisCK00 [560]
ApplicationAreas	dairies			BartakQ2 [54], Bartak02a [53]
ApplicationAreas	dairy	EscobetPQPRA19 [201]	PrataAN23 [509], HarjunkoskiMBC14 [279]	Groleaz21 [261]
ApplicationAreas	datacenter	HermenierDL11 [300]		Zahout21 [652], GalloguillosKSB19 [225], Madi-WambaLOBM17 [418], Letort13 [382], IfrimOS12 [320], LetortBC12 [383]
ApplicationAreas	datacentre		HurleyOS16 [319]	
ApplicationAreas	day-ahead market			
ApplicationAreas	deep space			HebradALLCMR22 [285]
ApplicationAreas	drone	MontemanniD23a [446], MontemanniD23 [447], Ham18 [273]		GuoZ23 [269], JuvinHL23a [331], Adelgren2023 [7], ShaikhK23 [547], EmdeZD22 [199], Astrand21 [35], Astrand0F21 [36], AntuoriHHEN21 [22], ZarandiASC20 [654], Ham18a [274]

Prolific Authors

Table 8: Co-Authors of Articles/Papers

Author	Nr Works	Nr Cites	Entries
J. Christopher Beck	49	701	LuoB22 [416], ZhangBB22 [658], TangB20 [573], RoshanaeiBAUB20 [521], TranPZLDB18 [597], TranVNB17 [599], TranVNB17a [600], CohenHB17 [154], BoothNB16 [114], KuhlB16 [365], TranAB16 [594], TranWDRFOVB16 [601], LuoVLBM16 [415], TranDRFWOVB16 [596], BajestaniB15 [43], KoschB14 [353], TerekhovTDB14 [581], LouieVNB14 [412], HeinzSB13 [294], HeinzKB13 [291], BajestaniB13 [42], TranTDB13 [598], HeinzB12 [290], TerekhovDOB12 [580], TranB12 [595], ZarandiB12 [213], KovacsB11 [356], BeckFW11 [66], HeckmanB11 [289], BajestaniB11 [41], WuBB09 [643], BidotVLB09 [94], CarchraeB09 [131], WatsonB08 [632], KovacsB08 [355], BeckW07 [73], Beck07 [64], KovacsB07 [354], Beck06 [63], CarchraeB05 [132], WuBB05 [642], BeckW05 [72], BeckW04 [71], BeckR03 [70], BeckPS03 [69], BeckF00 [68], Beck99 [62], BeckF98 [67], BeckDF97 [65]
Michela Milano	31	297	BorghesiBLMB18 [115], BonfiettiZLM16 [113], BridiBLMB16 [120], BridiLBBM16 [121], LombardiBM15 [399], BartoliniBBLM14 [69], BonfiettiLM14 [111], BonfiettiLBM14 [109], BonfiettiLM13 [110], LombardiM13 [406], LombardiMB13 [407], LombardiM12 [405], BonfiettiLBM12 [108], LombardiM12a [404], BonfiettiM12 [112], BonfiettiLBM11 [107], LombardiBMB11 [400], BeniniLMR11 [90], Milano11 [438], LombardiM10 [403], LombardiM10a [402], LombardiMRB10 [408], LombardiM09 [401], RuggieroBBMA09 [525], BeniniLMR09 [89], BeniniBGM06 [88], MilanoW06 [440], MilanoORT02 [439], LammaMM97 [377], BrusoniCLMM96 [123]
Andreas Schutt	27	322	YangSS19 [644], KreterSSZ18 [364], GoldwaserS18 [251], MusliuSS18 [455], KreterSS17 [363], YoungFS17 [646], GoldwaserS17 [250], SchuttS16 [543], SzerediS16 [570], KreterSS15 [362], EvenSH15 [203], EvenSH15a [204], SchuttFSW15 [542], ThiruvadyWGS14 [585], GuSSWC14 [266], SchuttFS13 [537], SchuttPS13a [536], GuSS13 [265], SchuttFSW13 [541], ChuGNSW13 [147], SchuttCSW12 [535], SchuttFSW11 [540], Schutt11 [534], SchuttW10 [544], abs-1009-0347 [539], SchuttFSW09 [538], SchuttWS05 [545]
Michele Lombardi	25	194	BorghesiBLMB18 [115], CauweleertLS18 [141], BonfiettiZLM16 [113], BridiBLMB16 [120], BridiLBBM16 [121], LombardiBM15 [399], BartoliniBBLM14 [69], BonfiettiLM14 [111], BonfiettiLBM14 [109], BonfiettiLM13 [110], LombardiM13 [406], LombardiMB13 [407], LombardiM12 [405], BonfiettiLBM12 [108], LombardiM12a [404], BonfiettiLBM11 [107], LombardiBMB11 [400], BeniniLMR11 [90], LombardiM10 [403], LombardiM10a [402], LombardiI10 [398], LombardiMRB10 [408], LombardiM09 [401], BeniniLMR08 [89], HooveGSL07 [609]
Peter J. Stuckey	24	453	YangSS19 [644], DemirovicS18 [177], KreterSSZ18 [364], MusliuSS18 [455], KreterSS17 [363], SchuttS16 [543], BlomPS16 [100], KreterSS15 [362], BurtLPS15 [124], SchuttFSW15 [542], BlomBPS14 [99], LipovetzkyBPS14 [394], GuSSWC14 [266], SchuttFS13 [537], SchuttPS13a [536], GuSS13 [265], SchuttFSW13 [541], SchuttCSW12 [535], GuSW12 [267], SchuttFSW11 [540], BandaSC11 [170], abs-1009-0347 [539], SchuttFSW09 [538], OhrimenkoSC09 [483]
John N. Hooker	19	1316	ElciOH22 [195], Hooker19 [312], Hooker17 [311], HookerH17 [314], HechingH16 [288], CireCH16 [150], HarjunkoskiMBC14 [279], CireCH13 [149], CobanH11 [153], CobanH10 [152], Hooker10 [310], Hooker07 [309], Hooker06 [308], Hooker05 [306], Hooker05a [307], Hooker04 [305], HookerO03 [313], HookerY02 [315], Hooker00 [304]
Emmanuel Hebrard	17	71	JuvinHHL23 [328], HebrardALLCMR22 [285], AntuoriHHEN21 [22], AntiguesHQT21 [32], GodetLHS20 [247], AntuoriHHEN20 [21], HebrardHJMPV16 [286], SimoninAHL15 [555], SialaAH15 [553], GrimesH15 [258], BessiereHMQW14 [93], SimoninAHL12 [554], BillautHL12 [95], GrimesH11 [257], GrimesH10 [256], GrimesHM09 [259], HebrardTW05 [287]
Pierre Lopez	17	90	JuvinHHL23 [328], JuvinHL23a [331], JuvinHL23 [330], HebrardALLCMR22 [285], JuvinHL22 [329], Polo-MejiaALB20 [503], NattafHKAL19 [466], NattafAL17 [463], NattafALR16 [464], SimoninAHL15 [555], NattafAL15 [462], SimoninAHL12 [554], BillautHL12 [95], LahimerLH11 [375], TroiethLL11 [602], LopezAKYG00 [410], TorresL00 [591]
Christian Artigues	16	203	FoveiaAA23 [206], PobilAK22 [502], HebrardALLCMR22 [285], AntiguesHQT21 [32], Polo-MejiaALB20 [503], NattafHKAL19 [466], NattafAL17 [463], NattafALR16 [464], SimoninAHL15 [555], NattafAL15 [462], SialaAH15 [553], SimoninAHL12 [554], NeronABCDD06 [481], DemasseyAM05 [176], AntiguesBF04 [30], AntiguesR00 [33]
Pierre Schaus	15	79	CauweleertDS20 [142], ThomasKS20 [586], HoundjiSW19 [316], CappartTSR18 [130], CauweleertLS18 [141], CappartS17 [129], CauweleertDMS16 [140], DejemeppeCS15 [173], GayHLS15 [229], GayHS15 [230], GayHS15a [231], HoundjiSWD14 [317], GaySS14 [232], SchausHMCMD11 [531], SchausD08 [530]
Helmut Simonis	15	154	ArmstrongGOS22 [27], ArmstrongGOS21 [26], AntunesABD20 [20], AntunesABD18 [19], HurleyOS16 [319], GrimesIOS14 [260], IfrimOS12 [320], SimonisH11 [562], Simonis07 [559], SimonisCK00 [560], Simonis99 [558], Simonis95 [561], Simonis95a [556], DincbasSH90 [184]
Nicolas Beldiceanu	13	274	Madi-WambaLOBM17 [418], Madi-WambaB16 [417], LetortCB15 [385], LetortCB13 [384], LetortBC12 [383], ClercqPBJ11 [151], BeldiceanuCDP11 [80], BeldiceanuCP08 [81], PoderB08 [500], BeldiceanuP07 [82], PoderBS04 [501], BeldiceanuC02 [79], AggounB93 [9]
Luca Benini	13	146	BorghesiBLMB18 [115], BridiLBBM16 [121], BridiLBM16 [120], BonfiettiLBM14 [109], BonfiettiLBM12 [108], BonfiettiLBM11 [107], LombardiBMB11 [400], BeniniLMR11 [90], LombardiMRB10 [408], RuggieroBBMA09 [525], BeniniLMR08 [89], BeniniBGM06 [88], LunardiBLRV20 [413], LaboriePSV18 [372], LaboriePSV18a [371], MolgareJoLS15 [11], VilimmLS15 [621], Laborie09 [370], BidotVLB09 [94], Baptis-
Philippe Laborie	12	513	

Limitations

- Limited coverage by OpenCitations
- Difficult to have local access to some publication types (book, incollection)
- Heavily biased towards publications in English
- More powerful NLP analysis of works possible?

Problem: Count for Most Cited Papers

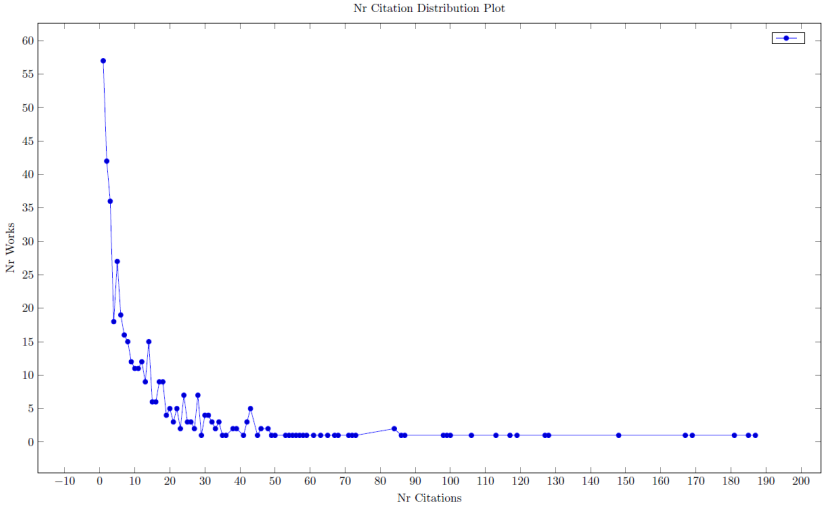
Table 9: Works from bibtex (Total 30)

Key	Authors	Title	LC	Cite	Year	Conference /Journal	Pages	Nr Cites	Nr Refs	b	c
JainM99 JainM99	A. Jain, S. Meeran	Deterministic job-shop scheduling: Past, present and future	Yes	[322]	1999	European Journal of Operational Research	45	490	150	1352	1753
HarjunkoskiMBC14 HarjunkoskiMBC14	I. Harjunkoski, Christos T. Maravelias, P. Bongers, Pedro M. Castro, S. Engell, Ignacio E. Grossmann, John N. Hooker, C. Méndez, G. Sand, J. Wassick	Scope for industrial applications of production scheduling models and solution methods	Yes	[279]	2014	Computers Chemical Engineering	33	381	176	1335	1649
BlazewiczDP96 BlazewiczDP96	J. Błażewicz, W. Domschke, E. Pesch	The job shop scheduling problem: Conventional and new solution techniques	Yes	[125]	1996	European Journal of Operational Research	33	344	127	1278	1762
HookerO03 HookerO03	John N. Hooker, G. Ottosson	Logic-based Benders decomposition	Yes	[313]	2003	Mathematical Programming	28	317	0	1347	1729
BaptistePN01 BaptistePN01	P. Baptiste, Claude Le Pape, W. Nuijten	Constraint-Based Scheduling	No	[50]	2001	Book	null	296	0	No	n/a
JainG01 JainG01	V. Jain, Ignacio E. Grossmann	Algorithms for Hybrid MILP/CP Models for a Class of Optimization Problems	Yes	[323]	2001	INFORMS Journal on Computing	19	279	23	1351	1738
AggounB93 AggounB93	A. Aggoun, N. Beldiceanu	Extending CHIP in order to solve complex scheduling and placement problems	Yes	[9]	1993	Mathematical and Computer Modelling	17	187	11	1247	1767
Hooker00 Hooker00	John N. Hooker	Logic Based Methods for Optimization: Combining Optimization and Constraint Satisfaction	No	[304]	2000	Book	null	185	0	No	n/a
Hooker07 Hooker07	John N. Hooker	Planning and Scheduling by Logic-Based Benders Decomposition	Yes	[309]	2007	Operations Research	29	181	19	1345	1715
HarjunkoskiG02 HarjunkoskiG02	I. Harjunkoski, Ignacio E. Grossmann	Decomposition techniques for multistage scheduling problems using mixed-integer and constraint programming methods	Yes	[278]	2002	Computers Chemical Engineering	20	169	11	1334	1733
BeldiceanuC94 BeldiceanuC94	N. Beldiceanu, E. Contejean	Introducing Global Constraints in CHIP	Yes	[78]	1994	Mathematical and Computer Modelling	27	167	8	1271	1765
LaborieRSV18 LaborieRSV18	P. Laborie, J. Rogerie, P. Shaw, P. Vilím	IBM ILOG CP optimizer for scheduling - 20+ years of scheduling with constraints at IBM/ILOG	Yes	[372]	2018	Constraints An Int. J.	41	148	35	1370	1610
Laborie03 Laborie03	P. Laborie	Algorithms for propagating resource constraints in AI planning and scheduling: Existing approaches and new results	Yes	[369]	2003	Artificial Intelligence	38	128	10	1369	1731
OhrimenkoSC09 OhrimenkoSC09	O. Ohrimenko, Peter J. Stuckey, M. Codish	Propagation via lazy clause generation	Yes	[483]	2009	Constraints An Int. J.	35	127	15	1417	1702
Ku816 Ku816	W. Ku, J. Christopher Beck	Mixed Integer Programming models for job shop scheduling: A computational analysis	Yes	[365]	2016	Computers Operations Research	9	119	17	1367	1630
Rodriguez07 Rodriguez07	J. Rodriguez	A constraint programming model for real-time train scheduling at junctions	Yes	[520]	2007	Transportation Research Part B: Methodological	15	117	6	1430	1716
LiW08 LiW08	H. Li, K. Womer	Scheduling projects with multi-skilled personnel by a hybrid MILP/CP benders decomposition algorithm	Yes	[386]	2008	Journal of Scheduling	18	113	31	1374	1708
CorreaLR07 CorreaLR07	Ayoub Insa Corrêa, A. Langevin, L. Rousseau	Scheduling and routing of automated guided vehicles: A hybrid approach	Yes	[158]	2007	Computers Operations Research	20	106	20	1296	1714
MengZRZL20 MengZRZL20	L. Meng, C. Zhang, Y. Ren, B. Zhang, C. Lv	Mixed-integer linear programming and constraint programming formulations for solving distributed flexible job shop scheduling problem	Yes	[435]	2020	Computers Industrial Engineering	13	100	62	1393	1574
BensanaLV99 BensanaLV99	E. Bensana, M. Lemaitre, G. Verfaillie	Earth Observation Satellite Management	Yes	[91]	1999	Constraints An Int. J.	7	99	0	1276	1752

OpenCitation Count Compared to Google Scholar

Key	Type	Google	OC	Ratio
JainM99	article	1116	490	2.28
HarjunkoskiMBC14	article	588	381	1.54
BlazewiczDP96	article	796	344	2.31
BaptistePN01	book	1039	296	3.51
AggounB93	article	502	187	2.68
LaborieRSV18	article	309	148	2.09
BensanaLV99	article	251	99	2.54
DincbasSH90	article	271	86	3.15
Thorsteinsson01	paper	205	67	3.06
DincbasSH88	paper	287	0	☹

Problem: Citation Count Distribution



Reuse Example: Survey of Car Sequencing

Table 9: Works from bibtex (Total 29)

Key	Authors	Title	LC	Cite	Year	Conference /Journal	Pages	Nr Cites	Nr Refs	b	c
BoysenFS09 BoysenFS09	N. Boysen, M. Fliedner, A. Scholl	Sequencing mixed-model assembly lines: Survey, classification and model critique	No	[2]	2009	European Journal of Operational Research	null	308	167	No	58
SolnonCNA08 SolnonCNA08	C. Solnon, V. Cung, A. Nguyen, C. Artigues	The car sequencing problem: Overview of state-of-the-art methods and industrial case-study of the ROADEF'2005 challenge problem	No	[21]	2008	European Journal of Operational Research	16	146	22	No	61
ParrelloK86 ParrelloK86	Bruce D. Parrello, Waldo C. Kabat	Job-Shop Scheduling Using Automated Reasoning: A Case Study of the Car-Sequencing Problem	Yes	[14]	1986	J. Autom. Reason.	42	74	0	46	66
Kis04 Kis04	T. Kis	On the complexity of the car sequencing problem	No	[9]	2004	Operations Research Letters	null	69	3	No	62
ReginP97 ReginP97	J. Régin, J. Puget	A Filtering Algorithm for Global Sequencing Constraints	Yes	[16]	1997	CP 1997	15	53	3	17	25
GottliebPS03 GottliebPS03	J. Gottlieb, M. Puchta, C. Solnon	A Study of Greedy, Local Search, and Ant Colony Optimization Approaches for Car Sequencing Problems	Yes	[7]	2003	EvoWorkshop 2003	12	46	5	13	24
HoevePRS06 HoevePRS06	Willem Jan van Hoeve, G. Pesant, L. Rousseau, A. Sabharwal	Revisiting the Sequence Constraint	Yes	[23]	2006	CP 2006	15	33	7	14	21
OzturkTHO13 OzturkTHO13	C. Öztürk, S. Tunali, B. Hnich, M. Arslan Ornek	Balancing and scheduling of flexible mixed model assembly lines	No	[13]	2013	Constraints An Int. J.	36	31	44	No	57
WarwickT95 WarwickT95	T. Warwick, Edward P. K. Tsang	Tackling Car Sequencing Problems Using a Generic Genetic Algorithm	No	[25]	1995	Evolutionary Computation	null	28	0	No	64
HindiP94 HindiP94	Khalil S. Hindi, G. Ploszajski	Formulation and solution of a selection and sequencing problem in car manufacture	No	[8]	1994	Computers Industrial Engineering	null	24	4	No	65
PerronS04 PerronS04	L. Perron, P. Shaw	Combining Forces to Solve the Car Sequencing Problem	Yes	[15]	2004	CPAIOR 2004	15	17	9	16	23
SialaHH155 SialaHH155	M. Siala, E. Hebrard, M. Huguet	A study of constraint programming heuristics for the car-sequencing problem	No	[20]	2015	Eng. Appl. Artif. Intell.	11	15	10	No	54
GolleRB14 GolleRB14	U. Golle, F. Rothlauf, N. Boysen	Iterative beam search for car sequencing	No	[6]	2014	Annals of Operations Research	null	15	15	No	55
HoevePRS09 HoevePRS09	Willem-Jan van Hoeve, G. Pesant, L. Rousseau, A. Sabharwal	New filtering algorithms for combinations of among constraints	No	[24]	2009	Constraints An Int. J.	null	13	8	No	59
MoyaCB19 MoyaCB19	I. Moya, M. Chica, J. Bautista	Constructive metaheuristics for solving the Car Sequencing Problem under uncertain partial demand	No	[12]	2019	Computers Industrial Engineering	1	8	44	No	50
SialaHH14 SialaHH14	M. Siala, E. Hebrard, M. Huguet	An optimal arc consistency algorithm for a particular case of sequence constraint	Yes	[19]	2014	Constraints An Int. J.	27	3	14	47	56
ZhangGWH17 ZhangGWH17	X. ZHANG, L. GAO, L. WEN, Z. HUANG	Parallel Construction Heuristic Combined with Constraint Propagation for the Car Sequencing Problem	No	[29]	2017	Chinese Journal of Mechanical Engineering	null	3	32	No	52
ArtiguesHM0W14 ArtiguesHM0W14	C. Artigues, E. Hebrard, V. Mayer-Eichberger, M. Siala, T. Walsh	SAT and Hybrid Models of the Car Sequencing Problem	Yes	[1]	2014	CPAIOR 2014	16	2	16	10	18
YuLZCLW22 YuLZCLW22	Y. Yu, X. Liu, T. Zhao, M. Cheng, L. Liu, W. Wei	Heuristic approaches for the car sequencing problems with block batches	No	[28]	2022	EURASIP Journal on Wireless Communications and Networking	null	2	37	No	48
DincbasSH88 DincbasSH88	M. Dincbas, H. Simonis, Pascal Van Hentenryck	Solving the Car-Sequencing Problem in Constraint Logic Programming	Yes	[4]	1988	ECAI 1988	6	0	0	12	26
Siala15 Siala15	M. Siala	Search, propagation, and learning in sequencing and scheduling problems. (Recherche, propagation et apprentissage dans les problèmes de séquencement et d'ordonnancement)	Yes	[18]	2015	INSA Toulouse, France	200	0	0	134	n/a

More Detailed Example Applications

- Production Planning and Scheduling
  - Siemens Energy, part of ASSISTANT project
- Outpatient Waitlist Management
  - Working within health service
- Elevator Maintenance Planning and Scheduling
  - Combination with simulation
- Selection of other problem types
  - Only summary slide shown

Outline

CP and Scheduling Literature Survey

ASSISTANT SE Use Case

Outpatient Waitlist Management

Elevator Maintenance Planning and Scheduling

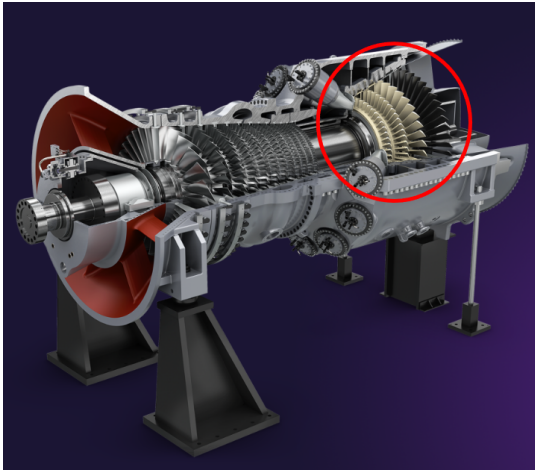
Other Applications

Summary

An Industrial Example

- ASSISTANT project Siemens Energy use case
- Mid/Long-term scheduling/production planning
- Realistic/not real data
- Rather complex constraint model
  - Multi-stage BOM
  - Alternative Process Paths
  - Alternative machines
  - Quality/cost based routing preferences
  - Potential outsourcing of certain steps
  - Machine specific calendars
  - Infeasible release/due date pairs
  - Calendar dependent speed reduction
  - Complex manpower constraints

Assistant Siemens Energy Use Case



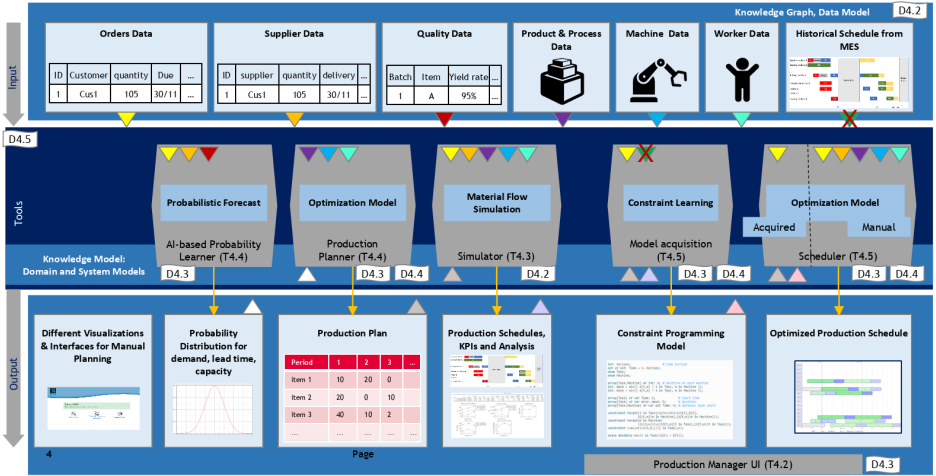
Use Case Scenarios

- Schedule *validation* of gas turbine blades and vanes manufacturing operations in Berlin plant
- Schedule *optimization* to manage short-term, mid-term and long-term load fluctuations
- Generate *Make-or-Buy proposals* for workload balancing within the manufacturing network

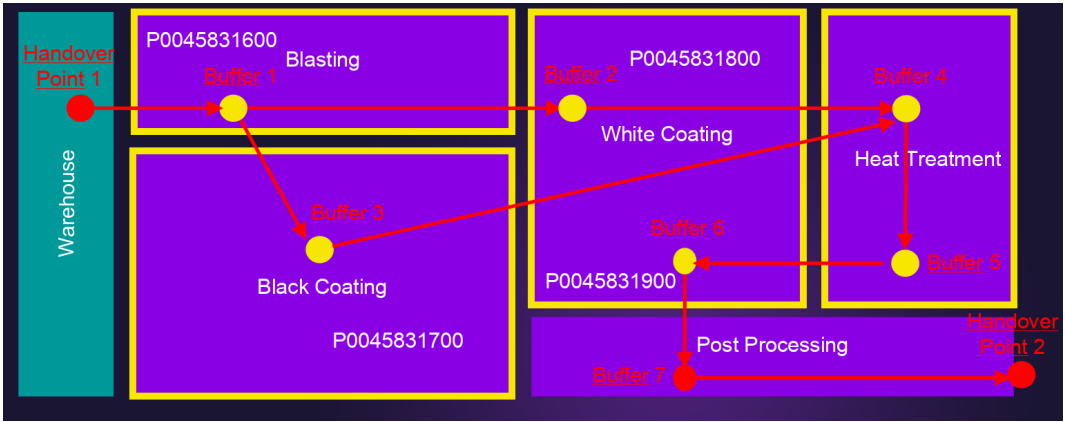
Digital Twin

Intelligent digital twin for process planning and scheduling

ASSISTANT



SE Product Routing



Datasets

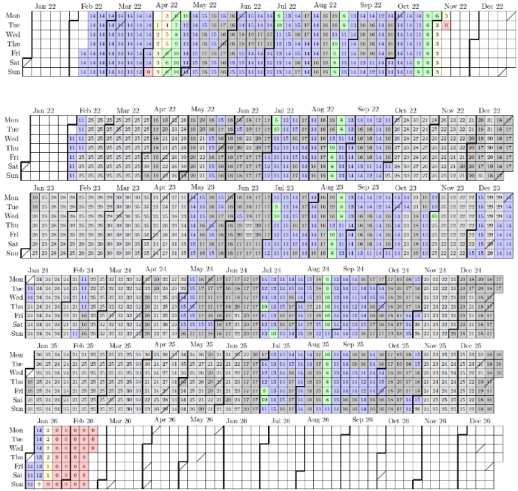
Full Scale Datasets

Berlin06: 96 orders, 9 months horizon, previous review

Berlin07: 450 orders, 4 years horizon

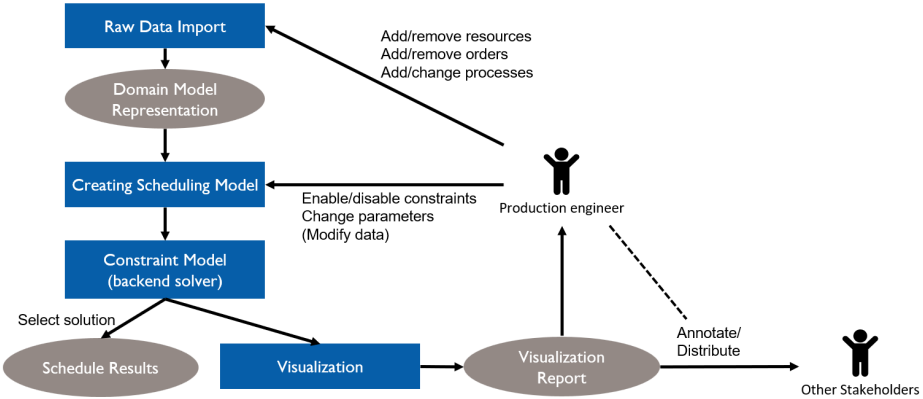
Berlin08: 559 orders, Christmas gap added

Berlin08a: 670 orders, filling gaps



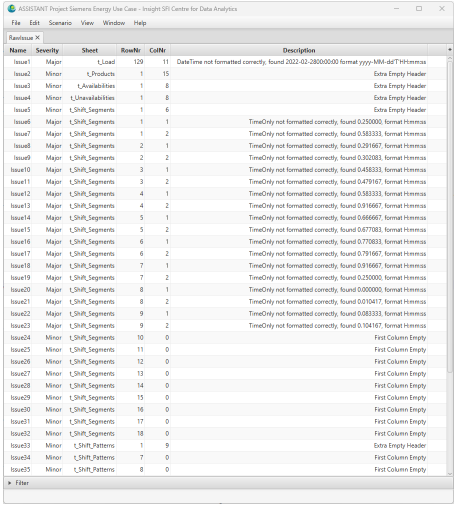
Value in cell indicates active orders
Yellow and red colors indicate low order volume

Optimizer High Level Structure

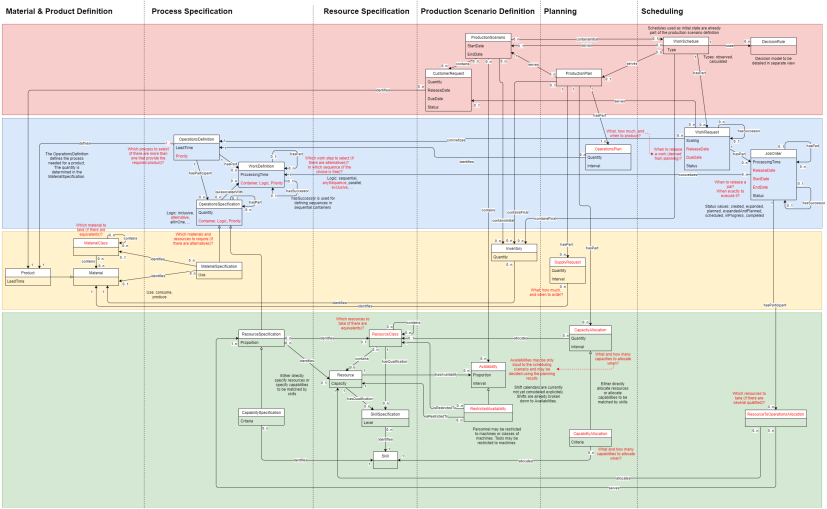


Raw Data - Manual Data Entry Causes Problems

- Raw data come from spreadsheet
  - 20 tabs
- Excel is a particularly bad input data format
- Realistic, not real data
- Created by hand/automatically from existing test scenarios
- Series of files Berlin01 - Berlin05 were too inconsistent to run
- Berlin06 still contains some errors
- Optimizer explains all issues that it finds



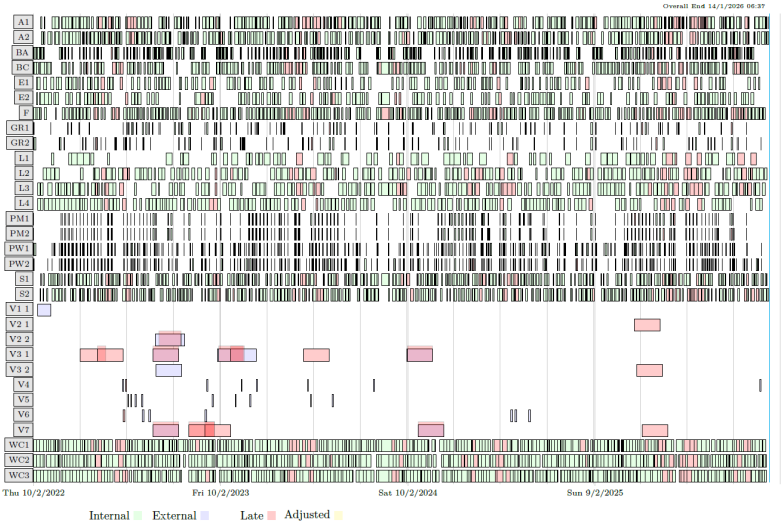
Domain Model - Knowledge Graph



ASSISTANT SE Use Case

Insight

Single Solution for Berlin 08a - Shows Only 20% of Tasks in Model

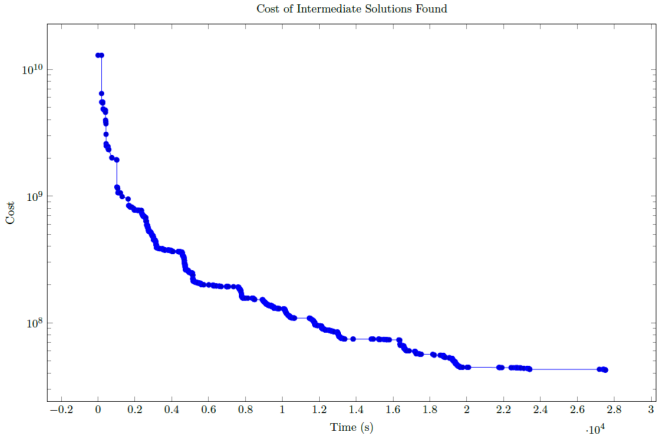


Implementation

- Requirement capture done inside project
- Data checking/cleaning most time consuming aspect
- Some specified functionality was rejected by Betriebsrat
- Built in Java
- Uses IBM's CPO back-end
- 120k LoC, 110k generated, 3k solver
- Outperforms both
  - Current in-house tool
  - Simulation based tool based on commercial simulator
- System installed at SE site, but not in daily use

CPO Keeps on Trucking

Figure 23: Evolution of Intermediate Solution Cost over Time, Dataset08, Pref 2 Options, time limit 8 hours



Conclusion

*"Within less than eight hours the **ASSISTANT** tools provided us thousands of manufacturing scenarios including different make-or-buy recommendations for making deliberate decisions on the way to proceed for strategic planning."*

Siemens SE final project review assessment

Outline

CP and Scheduling Literature Survey

ASSISTANT SE Use Case

Outpatient Waitlist Management
- Introduction
- Solution Approach
- Results
- Summary

Elevator Maintenance Planning and Scheduling

Other Applications

Summary

Joint work with...

- Mike O'Keeffe
- Adrian O'Leary
- Barry O'Sullivan
- At Insight Centre for Data Analytics, University College Cork

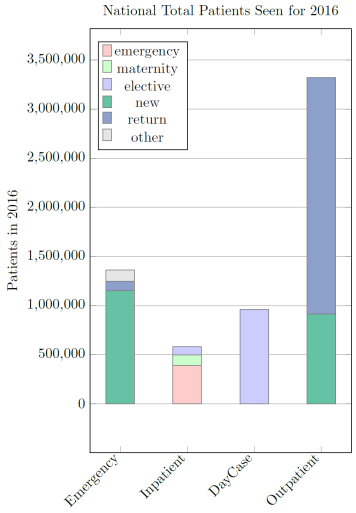
Real-World Problem

- Healthcare in Ireland
- Wait times for patients are out of control, even before Covid-19
- Longer wait times, poorer patient outcomes
- Critical to understand where to invest
- Currently: no tools to understand how changes affect performance

Research Challenges

- How to model hospital environment, many independent actors
- Deal with uncertain demand, and uncertain outcomes
- Understand where capacity is lost/not used

Hospital Services Overview



Data: HSE Management Data Report, Dec 2016

Outpatient Types

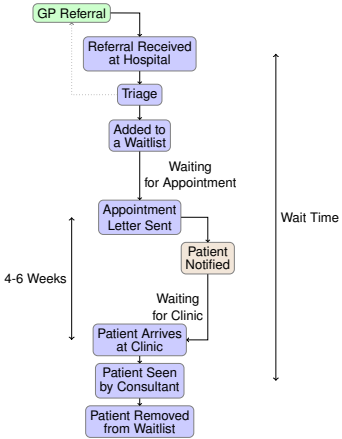
Rapid access seen within 14 days

Urgent seen within 28 days

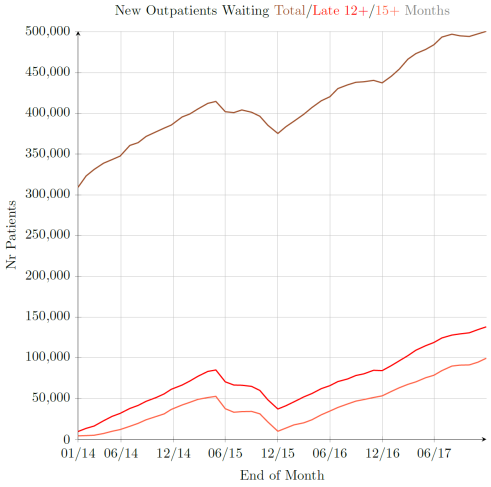
Soon seen within 3 months

Routine seen within 12 months (13 weeks, 15 months, 18 months?)

Outpatient Waitlist Management Process (Simplified)

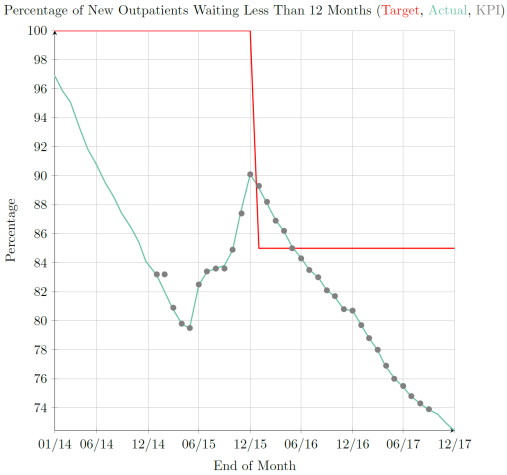


The Bad News



Data: NTPF

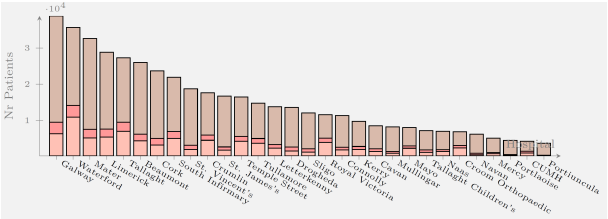
KPI: Waiting Time Percentage



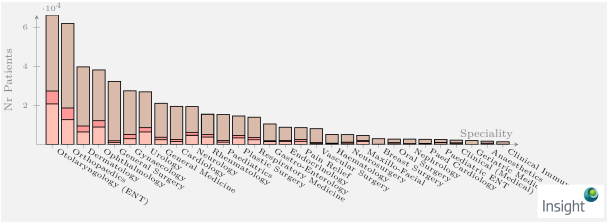
Data: HSE

A Near Universal Problem in Ireland

By Hospital



By Speciality



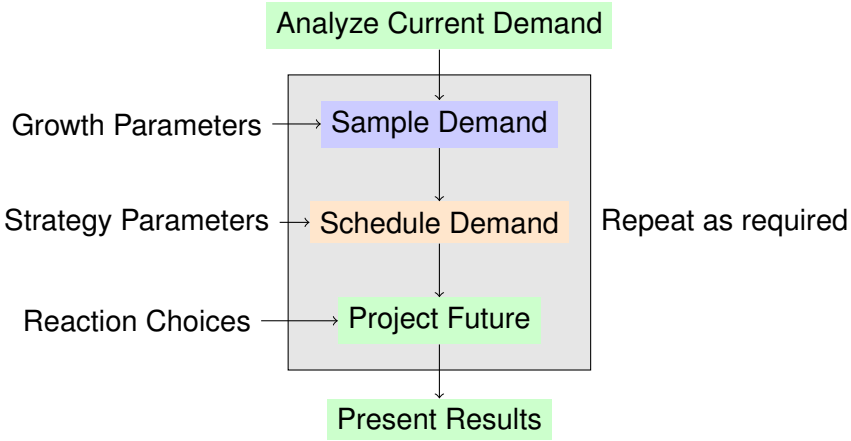
Our Brief

- Concentrate on Outpatients
- Develop strategy for appointment decision making
- What-if tool to understand the impact of decisions
- Support current stakeholders
- Not: Build automated appointment scheduling tool

The Appointment Conundrum

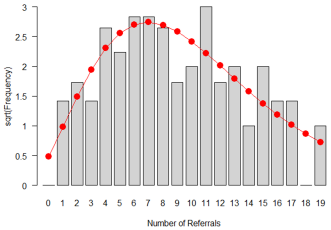
- We have to give ‘‘routine’’ appointment before knowing ‘‘urgent’’ demand
- There is limited capacity
- No overtime allowed (Croke Park agreement)
- How much capacity to set aside for urgent cases?
- How much overbooking is possible?

Methodology

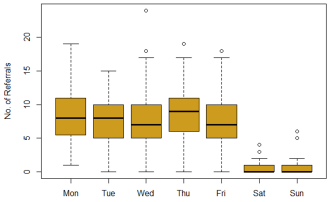


Demand Data (Not Public)

Received
Per Day

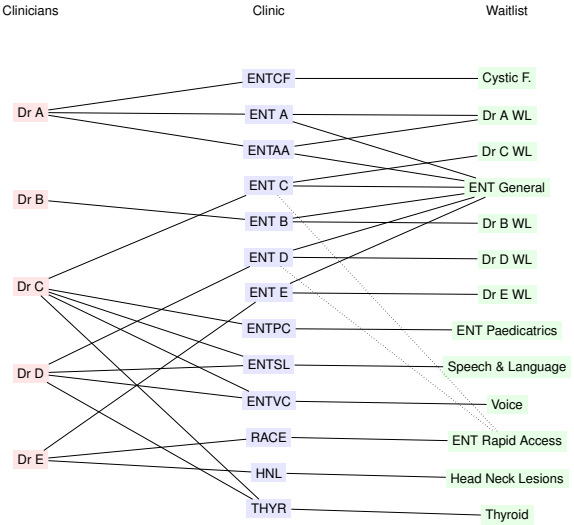


Received
Per Day of Week

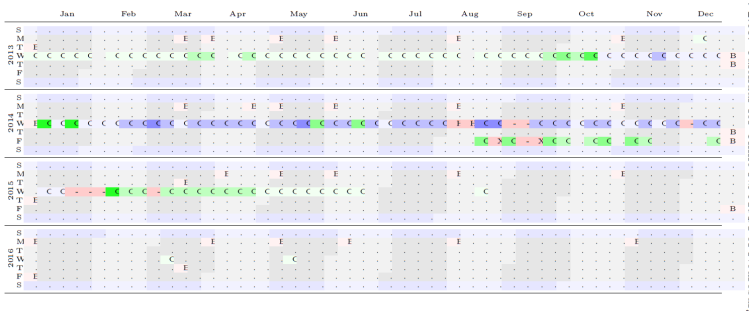


- Fitting distributions
  - Poisson, not good fit
  - Negative Binomial
- Limited Seasonality (unlike Emergency Department)

Waitlist/Clinic Model



Learning Capacity from Historical Data

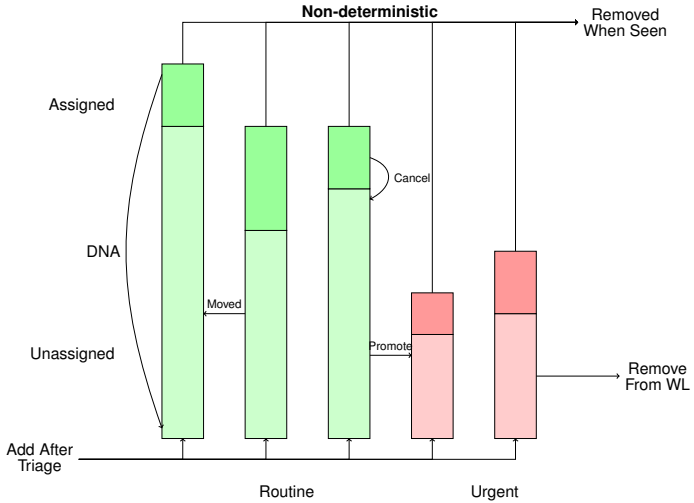


- Repeat frequency
- Capacity
- Cancellation frequency
- Replacement clinics

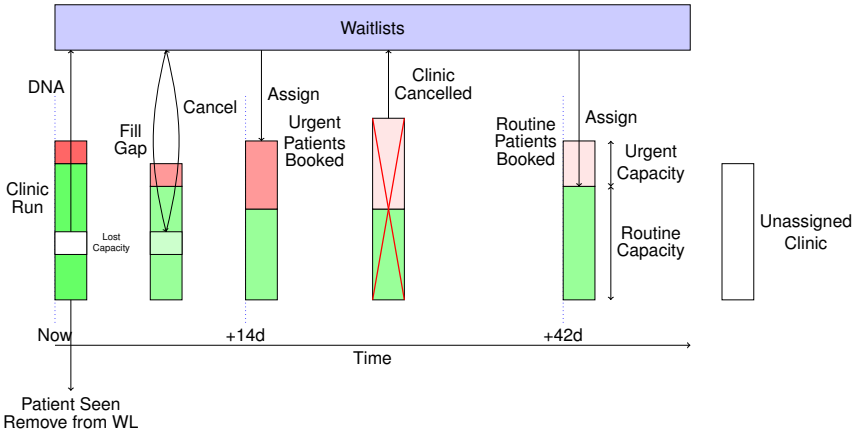
Optimization Problem

- Assign waiting patients to slots in clinics
- Use appropriate clinic for given patient
- Make appointments k_p days in advance
- Free and reuse slots when patients cancel
- Reschedule patients when clinic cancelled
- Do not change appointments otherwise
- Reserve u slots for urgent cases
- Solved for each day

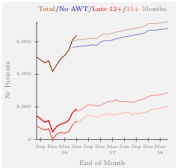
Waitlist Actions

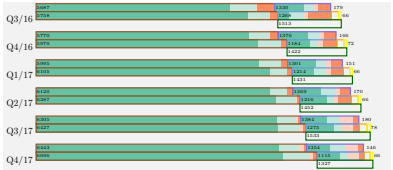


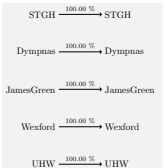
Clinic Allocation



Baseline Analysis, Management View





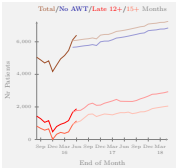


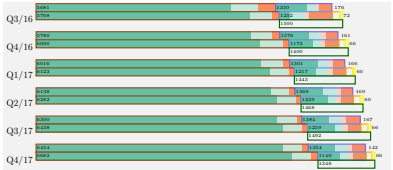
List/Category	Date	Patients Waiting	Breaching on Date	Patients in Breach	Avg	90%	Max	Waiting Time Distribution
All Urgent	One Month Ago	596	464	584	142.84	250	515	
	Now	432 ↘	302 ↘	428 ↘	90.72 ↘	128 ↘	228 ↘	
	In One Month	352 ↘	227 ↘	343 ↘	73.50 ↘	115 ↘	228 –	
	In Six Months	150 ↘	38 ↘	147 ↘	45.45 ↘	63 ↘	228 –	
	In One Year	109 ↘	11 ↘	51 ↘	33.19 ↘	56 ↘	70 ↘	
Routine	One Month Ago	5080	1635	4514	682.66	1215	1512	
	Now	5255 ↗	1737 ↗	4613 ↗	686.44 ↗	1219 ↗	1554 ↗	
	In One Month	5390 ↗	1801 ↗	4687 ↗	696.07 ↗	1226 ↗	1623 ↗	
	In Six Months	5845 ↗	2090 ↗	5315 ↗	743.39 ↗	1293 ↗	1718 ↗	
	In One Year	6196 ↗	2317 ↗	5737 ↗	787.76 ↗	1505 ↗	1835 ↗	

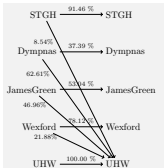
OWL2 (baseline): Thursday 4th August, 2016, at 22:58

Insight

Scenario: Balance Patients Between Hospitals



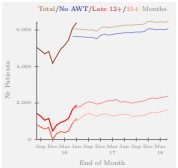


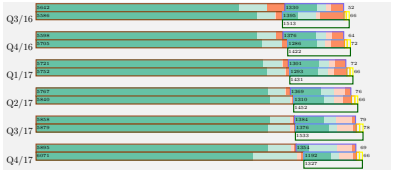


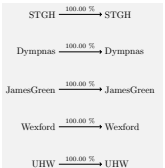
List/Category	Date	Patients Waiting	Breaching on Date	Patients in Breach	Avg	90%	Max	Waiting Time Distribution
All Urgent	One Month Ago	596	464	584	140.17	250	515	
	Now	412 ↘	281 ↘	408 ↘	84.85 ↘	106 ↘	200 ↘	
	In One Month	339 ↘	217 ↘	330 ↘	69.21 ↘	92 ↘	200 –	
	In Six Months	146 ↘	36 ↘	143 ↘	36.86 ↘	42 ↘	46 ↘	
	In One Year	112 ↘	15 ↘	109 ↘	33.42 ↘	37 ↘	41 ↘	
Routine	One Month Ago	5080	1635	4511	608.66	718	796	
	Now	5269 ↗	1758 ↗	4629 ↗	609.15 ↗	743 ↗	797 ↗	
	In One Month	5390 ↗	1784 ↗	4661 ↗	612.68 ↗	757 ↗	798 ↗	
	In Six Months	5870 ↗	2111 ↗	5326 ↗	632.37 ↗	781 ↗	803 ↗	
	In One Year	6188 ↗	2325 ↗	5726 ↗	632.10 ↗	780 ↗	803 –	

OWL2 (balanced; ENTMH can serve all hospitals with overall capacity): Thursday 4th August, 2016, at 17:02

Scenario: Reduce DNA (Did not attend) to 5%

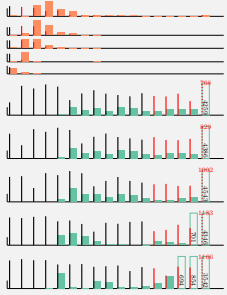






List/Category	Date	Patients Waiting	Breaching on Date	Patients in Breach	Avg	90%	Max
All Urgent	One Month Ago	596	464	584	142.64	250	515
	Now	404 ↘	300 ↘	401 ↘	91.83 ↘	128 ↘	228 ↘
	In One Month	301 ↘	199 ↘	293 ↘	74.12 ↘	120 ↘	228 ↔
	In Six Months	130 ↘	27 ↘	127 ↘	42.88 ↘	56 ↘	228 ↔
	In One Year	92 ↘	8 ↘	21 ↘	30.87 ↘	47 ↘	64 ↘
Routine	One Month Ago	5080	1635	4509	655.06	1154	1473
	Now	5238 ↗	1735 ↗	4606 ↗	658.91 ↗	1161 ↗	1490 ↗
	In One Month	5346 ↗	1796 ↗	4678 ↗	668.77 ↗	1166 ↗	1540 ↗
	In Six Months	5591 ↗	1968 ↗	5145 ↗	714.68 ↗	1277 ↗	1669 ↗
	In One Year	5766 ↗	2061 ↗	5314 ↗	757.54 ↗	1471 ↗	1779 ↗

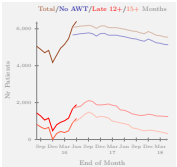
Waiting Time Distribution

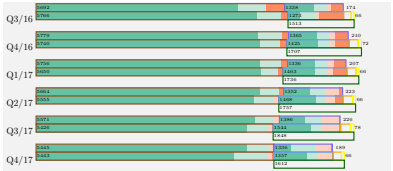


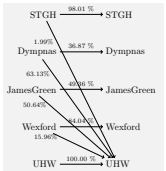
OWL2 (DNA 5 percent for routine patients): Thursday 4th August, 2016, at 16:59

Insight

Scenario: Add Capacity







List/Category	Date	Patients Waiting	Breaching on Date	Patients in Breach	Avg	90%	Max	Waiting Time Distribution
All Urgent	One Month Ago	596	464	583	141.70	248	513	
	Now	424 ↘	301 ↘	421 ↘	90.75 ↘	130 ↘	231 ↘	
	In One Month	335 ↘	210 ↘	330 ↘	71.78 ↘	123 ↘	231 –	
	In Six Months	146 ↘	29 ↘	140 ↘	38.77 ↘	36 ↘	231 –	
	In One Year	117 ↘	0 ↘	0 ↘	26.30 ↘	30 ↘	30 ↘	
Routine	One Month Ago	5080	1644	4508	540.10	654	672	
	Now	5268 ↗	1734 ↗	4624 ↗	534.89 ↘	653 ↘	672 –	
	In One Month	5409 ↗	1795 ↗	4701 ↗	531.09 ↘	653 –	672 –	
	In Six Months	5610 ↗	1867 ↗	5134 ↗	514.78 ↘	629 ↘	672 –	
	In One Year	5454 ↘	1573 ↘	5004 ↘	474.74 ↘	547 ↘	566 ↘	

OWL2 (25 New Patients per Week from 1/10/2016): Thursday 4th August, 2016, at 17:06

Insight

Summary

- Presented case study from Irish health system
- Strategy for outpatient appointments
- Mix of analytics, simulation, and optimization
- Nation-wide analysis of available data
- What-if tool for selected departments

Outline

Joint work with...

- Mark Antunes, Vincent Armant, Kenneth N. Brown, Gabriel G. Castane, Daniel Desmond, Guillaume Escamocher, Michele Garraffa, Anne-Marie George, Diarmuid Grimes, Mike O'Keefe, Yiqing Lin, Barry O'Sullivan, Cemalettin Ozturk, Luis Quesada, Mohamed Siala, Helmut Simonis and Nic Wilson

Real World Problem

- Manufacturing Industry, after sales support
- Maintenance is crucial for safety/availability of product
- Preventive/Predictive/Reactive Maintenance influence each other
- How to organize service, what to do?

Research Challenge

- How to plan/schedule if events interrupt planned work
- How to use predictive maintenance to avoid problems before they occur
- What is the right problem decomposition?

Travelling Repair Person (TRP)

- Providing service for devices at customer premises
- Planned preventive maintenance and testing, regular visits
- Technicians travel to multiple, but few customers per day
- Unplanned repair work after faults, response-time critical
- Service times quite variable
- Impact of skills and local knowledge

Why is this important? (1)

Law and Crime

Lift firm Otis fined HK$320,000 over Hong Kong mall escalator accident that injured 18

Company, which pleaded guilty to four summonses, could have discovered safety issues with escalator three months before malfunction, court told

Jasmine Siu

Published: 8:15pm, 9 Mar, 2018

Why is this important? (2)

BIG STORY 10 APRIL 5, 2016 / 6:40 AM / 3 YEARS AGO

Schindler sells Japanese business to Otis after accident

2 MIN READ

ZURICH (Reuters) - Elevator maker Schindler is selling its Japanese business to United Technologies' Otis unit after its new installations in the country were halted following a 2006 accident.

Source: REUTERS

Why is this important? (3)

Source: By Chris6d - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=78201640

High-level View

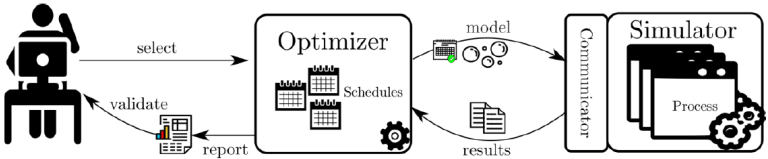


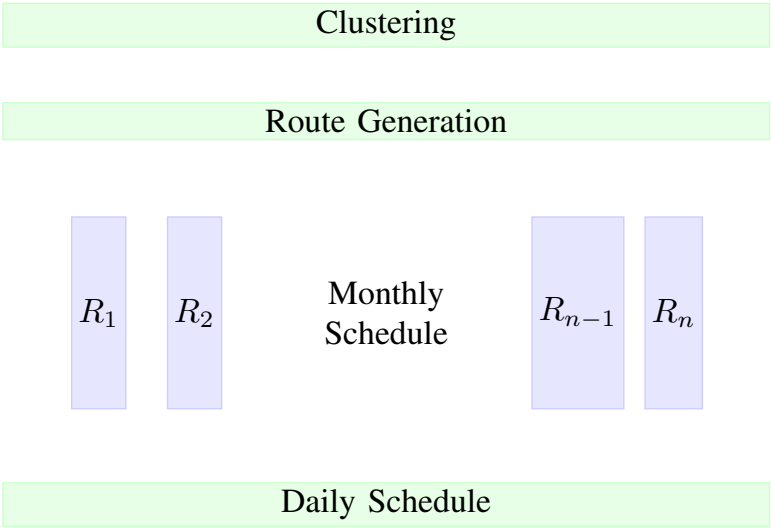
Figure 1 High level overview of the framework

- Optimizer deals with planning, load balancing, efficient schedules
- Simulator explores how to react to changes
- Simulator also provides one result as assumed reality

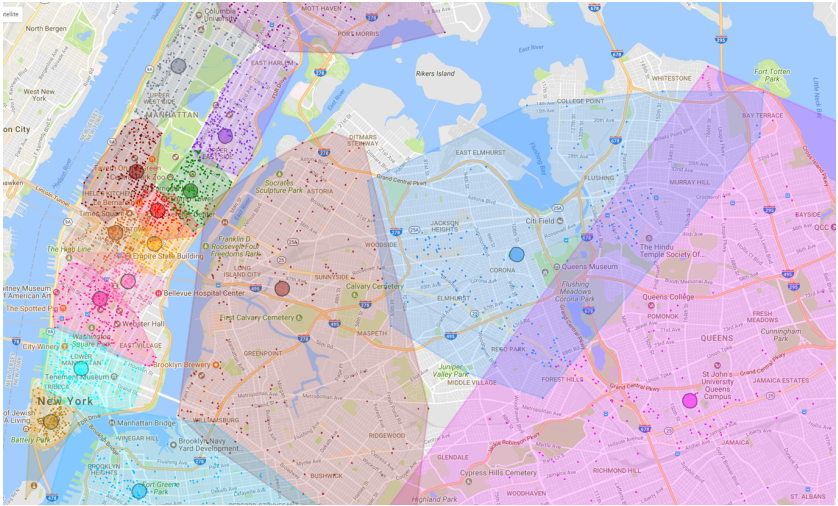
Optimizer Design

- Infeasible to build homogenuous model for complete problem
- Added business process constraint
  - Technicians should be responsible for ‘‘their’’ buildings
  - Improves service quality
  - Customers see familiar face
- All work in one building should be performed by the same engineer, if possible
- Engineers should be assigned compact areas of work
- Balanced workload within the same depot

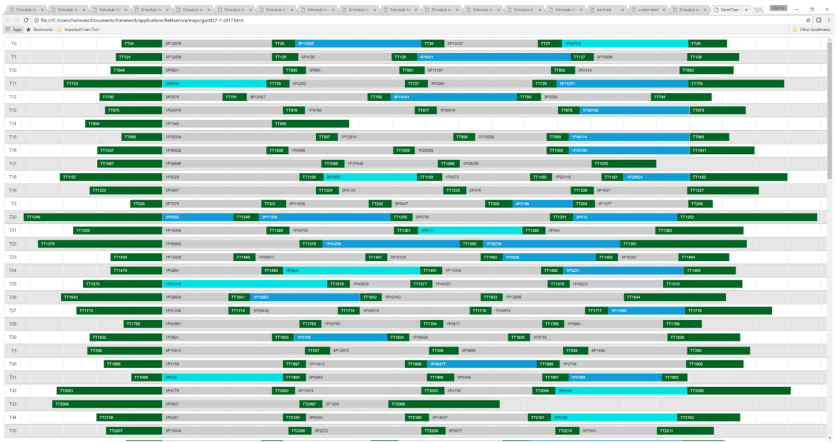
Optimizer Decomposition



Clustering and Depot Assignment



Scheduling: One Day of Monthly Plan



Methods Used

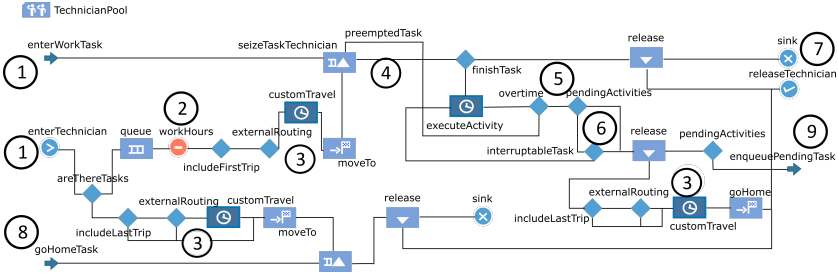
Clustering Connected components on generated graph

Routing Which places to visit in one trip

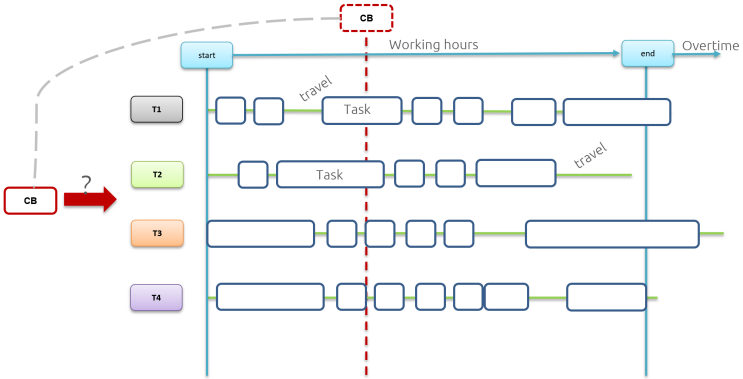
- Core MIP Model
- Iterative MIP inside Clustering
- Two stage grouping of locations to reduce expected travel
- Local Search

Scheduling Dynamic Programming and Set Partitioning

Simulator Process Modelling



Dealing with Unplanned Callbacks



- Who is dealing with the callback?
- How to adjust the schedule after callback?

Use Cases

- Compare variants of problem to understand impact of changes
- Examples
  - Where to place depots and their area?
  - How many technicians are needed in which depots?
  - Should technicians do both planned and unplanned work?
  - When is overtime the better choice?

Scenario Evaluation: KPI Comparison

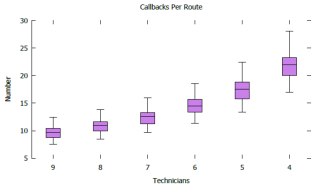


Figure 6 Callbacks per route (technician)

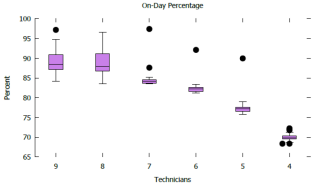


Figure 7 Percentage of tasks performed per tasks

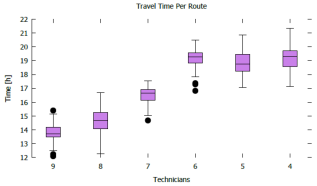


Figure 9 Travel time per technician

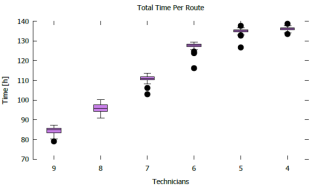
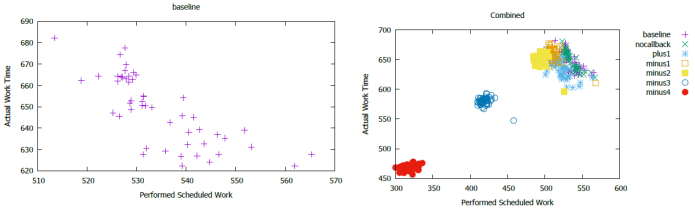


Figure 8 Total time per technician

Scenario Evaluation: Qualitative Differences



- On left, each point shows the outcome of one month of optimization+simulation
- On right, compare outcomes for different scenarios, clear clustering of results

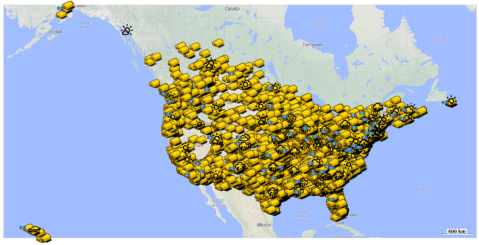
Challenges: Data

- We need company internal data to understand problem
- Problem for publication, for continued work
- Open data as alternatives
  - New York City
    - 76,000 elevators with locations
  - Toronto, ON
    - 40,000 elevators
    - Inspection dates, outcomes
    - Accident and injury reports

Challenges: Scalability

Data source	Locations
Arby's	3347
Burger King	7269
Dairy Queen	5189
Dominos Pizza	3261
Dunking donuts	8134
KFC	5637
Little Caesars	4019
Mc Donald's	15474
Papa John's	3089
Pizza Hut	6672
Starbucks	11788
Subway	2213
Taco bell	6996
Wendy's	6140
Walmart	22212

- 136663 total locations (cleaned noisy data)
- 1 Unit per location
- 63 areas (US + Canada)
- Experiments definition:
  - 1, 10, 100, 1000, 10000 technicians per area



Challenges: Tools and Results

- We provide research and experimental software
- **Not** a solution
- End-user would like applicable results
- Managing expectations is important

Conclusions

- We presented the Travelling Repair Person Problem
- Important as an industrial problem
- Interesting as a research challenge
- We use combination of optimization and simulation to deal with novel properties of problem
- System transferred to customer in 2019

Outline

Other Noteworthy Applications

- NVD LoadBuilder
- Boliden Tara Mines Dewatering
- Dental School Timetabling
- Irish Naval Service Rostering
- Data Centre Load Consolidation
- Scheduling with Time Variable Energy Prices
- Characterizing EDF Power Plants with Timeseries Constraints
- Optical Network Design
- Supplier Selection Problem
- Optimizing UCC's CHP Plant Operation
- CP Conference Paper Assignment Tool

NVD LoadBuilder

- Real-World Problem
  - Deliver cars/vans from factory/ports to dealers
  - Group cars into loads for joint delivery
  - Using specialized transporters with complex configurations
  - Balance distance travelled, utilization of fleet, priority of orders
- Status
  - In daily use at customer since 2020
  - Start-up company CMC to further develop tool

- Research Challenges
  - Vehicle routing problem with complex capacity constraints
  - Decide which cars to deliver today
  - What impact does this have tomorrow
  - Explaining solutions to end-user
- Solution Approach
  - Decomposition
  - MIP, Constraint Programming, Local Search, Data Analytics

Boliden Tara Mines Dewatering

- Real-World Problem
  - When/how to pump water out of mine
  - Multiple pumps, reservoirs
  - Electricity cost major cost factor
  - Safe operation of mine paramount
- Status
  - Student-led project with DCU
  - Paper at AAAI 2016
  - Major flooding event in 2021

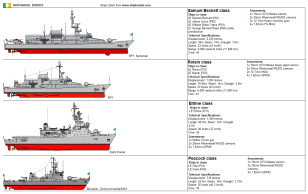
- Research Challenges
  - Scheduling with uncertain energy prices (real-time tariff)
  - Uncertain water ingress depends on operations
  - Capacity (min/max) constraints for storage
- Solution Approach
  - Electricity price prediction
  - Optimization

Dental School Timetabling

- Real-World Problem
  - Change time table during period of teaching capacity increase
  - Previous schedule no longer feasible
  - Multiple courses share same lab space (dental chairs) at the same time
  - Hard capacity limits on available resources and time slots
- Status
  - Used by dental school during transition period
  - Paper in IAAI 2013, AI Mag 2014

- Research Challenges
  - Very different from standard timetabling problem
  - Hard/soft capacity constraints
  - Tool cleaning setup time constraints
- Solution Approach
  - Optimization
  - Flexible prioritization of constraints

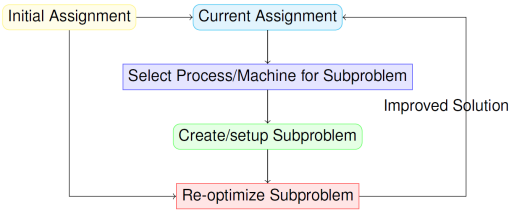
Irish Naval Service Yearly Rostering



- Real-World Problem
  - Decide which ships are performing which type of duty over the year
  - Budget limitations on total time at sea
  - Fair share of work across fleet
  - Fixed maintenance periods for certain ships
  - Special events (flotilla exercises, detached duty)
- Status
  - Prototype results produced for service

- Research Challenges
  - Finding the best tool and model for problem
  - Balanced assignment under budget constraints
  - Provide consistent force levels over whole year
  - Fair assignment of work/rest days across fleet
- Solution Approach
  - Optimization

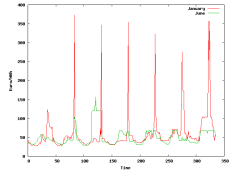
Data Centre Load Consolidation



- Real-World Problem
  - Move virtual machines between servers in a data centre
  - Balance/concentrate workload on multiple resource types
  - Extend to multiple data centres across world
- Status
  - 2nd place in Google Roadef/Euro Challenge 2012
  - Multiple papers

- Research Challenges
  - Reassignment problem
  - Multi-bin packing constraints
  - Large neighbourhood search to deal with problem size
- Solution Approach
  - Optimization
  - New tools/propagators

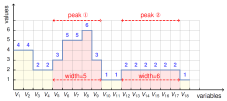
Scheduling with Time Variable Energy Prices



- Real-World Problem
  - How do time-variable electricity prices affect scheduling of use
  - Uncertainty of prices, sudden peak prices common in Ireland
  - In most cases, we have to commit to production before price is known
  - Deal with risk/possible rewards
- Status
  - Multiple papers
  - Continued work on price prediction with industry

- Research Challenges
  - Can we use time variable electricity prices to our advantage?
  - Which properties should a price prediction model have to help with scheduling?
  - Can we tune price prediction for the use case it is intended for?
- Solution Approach
  - Machine Learning
  - Optimization

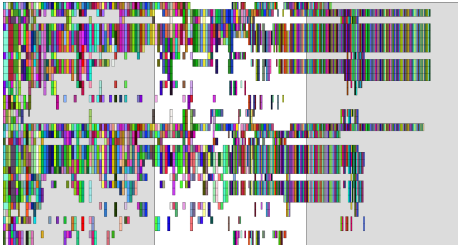
Characterizing EDF Power Plants



- Real-World Problem
  - Unit Commitment Model for electricity supply
  - Decide which units to run when to satisfy demand/minimize cost
  - Change of production for different units is limited over time
  - Very error-prone integration into global model
- Status
  - Joint work with IMT-Atlantique, EDF Research
  - Series of papers on time-series constraints, Volume II of Global Constraint Catalog

- Research Challenges
  - Can we characterize the production limits of power plants as time-series constraints?
  - Learn constraints from historical data (planned/actual)
  - Create model of individual plants to describe their capabilities
  - Find redundant constraints to overcome limits of propagation
- Solution Approach
  - Machine Learning
  - Automata constraints
  - Generated code for propagators

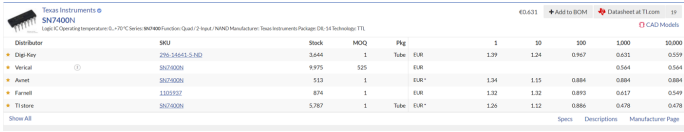
Optical Network Design



- Real-World Problem
  - Core optical network design
  - Different from traditional IP network design
  - Define paths from source to sink
  - Use multiple frequency (light) bands over same fibre
- Status
  - paper ICTAI 2014

- Research Challenges
  - Modelling Choices
  - Amount of propagation achieved
  - Scalability of methods
- Solution Approach
  - Global Constraints

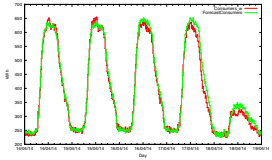
Supplier Selection Problem



- Real-World Problem
  - Which suppliers to select to provide list of components
  - Limit number of suppliers by ordering multiple items from same supplier
  - Price/lead time/quality of service are competing objectives
- Status
  - Work with industry partner
  - Paper in Annals of Operations Research

- Research Challenges
  - How do we learn which choices are preferred
  - Difficult to assign fixed weights to different aspects of solution quality
  - Iterative, interactive learning of preferences
- Solution Approach
  - Preference Learning
  - Optimization

Optimizing UCC's CHP Plant Operation



- Real-World Problem
  - When to run UCC's CHP plant to create electricity/heat on-site
  - Needs demand forecast for heat and electricity
  - Uncertain Real-time grid electricity price
  - Heat and electricity demand of campus not in sync
- Status
  - Tested for several weeks with operator of plant
  - Part of EU Discipl project

- Research Challenges
  - Heat and Electricity Demand prediction for campus
  - Price prediction for real-time grid price
  - Integration of plant operational constraints
  - Wider impact of heating strategy on campus
- Solution Approach
  - Machine Learning
  - Optimization

CP Conference Paper Assignment Tool

- Real-World Problem
  - Which reviewers to assign to papers
  - Consider bids by reviewers, avoid assigning unwanted papers
  - Deal with reviewers shared between multiple tracks
  - Balance assignment between reviewers
  - Allow pre-assignment, specific capacity constraints
- Status
  - Joint work with Data61, INRA
  - Used in 2020, 2021
  - Paper at ModRef 2020
- Research Challenges
  - Fair treatment of papers and reviewers
  - Finding mechanisms to allow Program Chair to control process
  - Not a black-box assignment
  - Integration with easychair
- Solution Approach
  - Optimization

Outline

Summary

- Teaser for CP & Scheduling Survey
  - Live at `https://hsimonis.github.io/pthg24/`
- Provided details on some application work at Insight
- Shows the impact of practical problems on basic research
- Research can have a real impact
- It takes time to do application based research