# Applications of Constraint Programming

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**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 Demirovič, 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.

# 1 CP and Scheduling Literature Survey

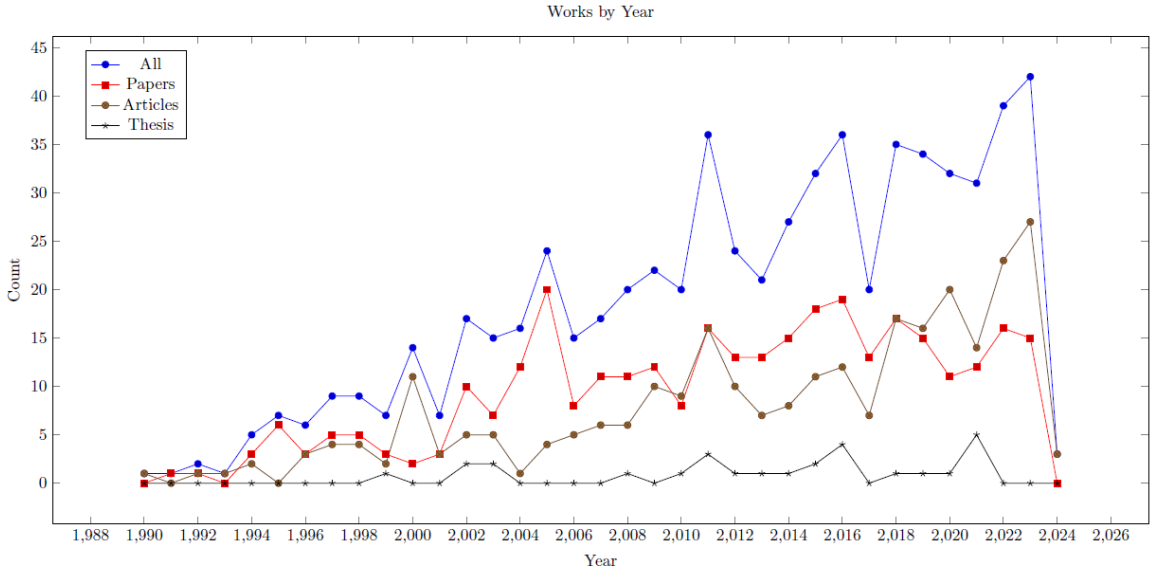
**A Survey of the Existing Literature**

- 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

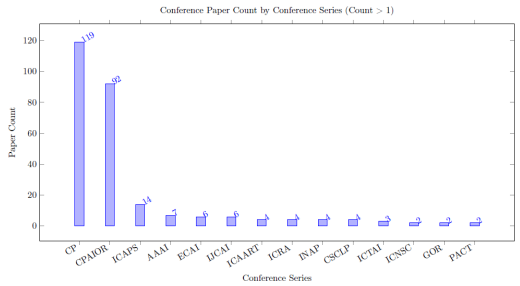
## Methodology

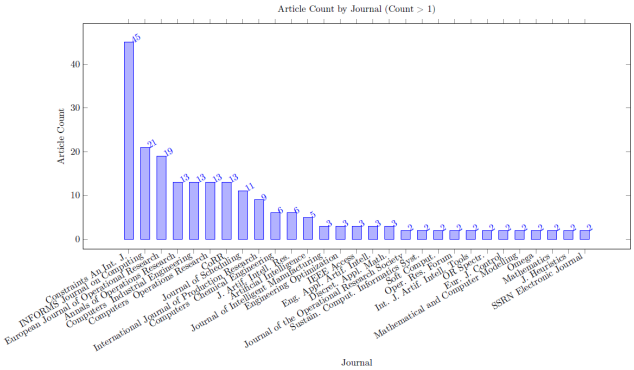
- Manually curated list of works, somewhat inclusive
- Starting with bibtex files
- Citation links through OpenCitations (open access)
- Content analysis on local copies of pdf files
- Closure of domain by analyzing missing cited and citing works
- Limited manual analysis of works (datasets, code)
- 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. Talmre | 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. Pastore, 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 |
| FatemiAnarakiTFV23 FatemiAnarakiTFV23 | 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, activity, precedence, preempt, scheduling, machine | TCSP | cycle, span constraint, cumulative, disjunctive, table constraint | 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 Propagation 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 | real-world, random instance | 0 | (y) | | n | [628] | FJS | - | 14 | 620 |
| YuraszeckMC23 YuraszeckMC23 [649] | A competitive constraint programming approach for the group shop scheduling problem | CP Opt | github, benchmark | 0 | ref | | n | - | GSSP | noOverlap endBeforeStart | 15 | 633 |

## Extracted Features: Application Areas

Table 16: Works for Concepts of Type ApplicationAreas

| Type | Keyword | High | Medium | Low |
|---|---|---|---|---|
| ApplicationAreas | COVID | GuoZ23 [269] | GelbingerKKMMW21 [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], Lombardi10 [398], Laborie09 [370], KovacsB08 [355], KrogtLPHJ07 [608], MartinPY01 [427], SimonisCK00 [560], GrulianK98 [264], Darby-DowmanLMZ97 [163], Wallace96 [625], Simonis95 [557], SimonisC95 [561] |
| ApplicationAreas | automotive | | GuoZ23 [269], YuraszeckMPV22 [650], EmdeZD22 [199], Groleaz21 [261], LimtanyakulS13 [393], SunLYL10 [567], Lombardi10 [398], BarlattCG08 [52], Schildw00 [532] | PovedaAA23 [506], NaderiRR23 [460], CzerniachowskaWZ23 [159], NaderiBZ22 [457], NaderiBZ22a [456], AntuoriHHEN21 [22], HubnerGSV21 [318], AbreuAPNM21 [166], KoehlerBFFHPSSS21 [348], VlkHT21 [623], BarzegaranZP20 [61], GelbingerMM19 [236], abs-1911-04766 [235], BonfiettiZLM16 [113], Slala15a [552], SchnellH15 [533], AlesioNBG14 [181], HarjunkoskiMBC14 [279], BeninlBGM06 [88], KovacsV06 [360], Wallace96 [625] |
| ApplicationAreas | cable tree | KoehlerBFFHPSSS21 [348] | | |
| ApplicationAreas | car manufacturing | | AntuoriHHEN21 [22] | BelditceanuC94 [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], CauwelaertDMS16 [140], Dejemeppe16 [172], DejemeppeCS15 [173], NovasH12 [476], CorreaLR07 [158], LimRX04 [389] |
| ApplicationAreas | crew-scheduling | ZarandiASC20 [654], PourDERB18 [505] | BourreauGGLT22 [118], Zahout21 [652], GombolayWS18 [253], Mason01 [429], Touralvane95 [593] | 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], WuBB09 [643], MilanoW06 [440], BelditceanuC02 [79], JainG01 [323], SimonisCK00 [560] |
| ApplicationAreas | dairies | | | Bartak02 [54], Bartak02a [53] |
| ApplicationAreas | dairy | EscobetPQPRA19 [201] | PrataAN23 [509], HarjunkoskiMBC14 [279] | Groleaz21 [261] |
| ApplicationAreas | datacenter | HermenierDL11 [300] | | Zahout21 [652], GalleguillosKSB19 [225], Madi-WambaLOBM17 [418], Letort13 [382], IfrimOS12 [320], LetortBC12 [383] |
| ApplicationAreas | datacentre | | HurleyOS16 [319] | |
| ApplicationAreas | day-ahead market | | | |
| ApplicationAreas | deep space | | | HebrardALLCMR22 [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], KuB16 [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], CarchraeBF05 [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 [60], 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], MilanoW09 [441], BeniniLMR08 [89], BeniniBGM06 [88], MilanoW06 [440], MilanoORT02 [439], LammaMM97 [377], BrusoniCLMMT96 [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], SchuttFS13a [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], CauwelaertLS18 [141], BonfiettiZLM16 [113], BridiBLMB16 [120], BridiLBBM16 [121], LombardiBM15 [399], BartoliniBBLM14 [60], 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], HoeveGSL07 [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], SchuttFS13a [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], ArtiguesHQT21 [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], TrojetHL11 [602], LopezAKYG00 [410], TorresL00 [591] |
| Christian Artigues | 16 | 203 | PovedaAA23 [506], PohlAK22 [502], HebrardALLCMR22 [285], ArtiguesHQT21 [32], Polo-MejiaALB20 [503], NattafHKAL19 [466], NattafAL17 [463], NattafALR16 [464], SimoninAHL15 [555], NattafAL15 [462], SialaAH15 [553], SimoninAHL12 [554], NeronABCDD06 [481], DemasseyAM05 [176], ArtiguesBF04 [30], ArtiguesR00 [33] |
| Pierre Schaus | 15 | 79 | CauwelaertDS20 [142], ThomasKS20 [586], HoundjiSW19 [316], CappartTSR18 [130], CauwelaertLS18 [141], CappartS17 [129], CauwelaertDMS16 [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], SimonisC95 [561], Simonis95 [557], Simonis95a [556], DincbasSH90 [184] |
| Nicolas Beldiceanu | 13 | 274 | Madi-WambaLOBM17 [418], Madi-WambaB16 [417], LetortCB15 [385], LetortCB13 [384], LetortBC12 [383], ClercqPBJ11 [151], BeldiceanuCDPT11 [80], BeldiceanuCP08 [81], PoderB08 [500], BeldiceanuP07 [82], PoderBS04 [501], BeldiceanuC02 [79], Aggoun93 [9] |
| Luca Benini | 13 | 146 | BorghesiBLMB18 [115], BridiBLMB16 [120], BridiLBBM16 [121], BonfiettiLBM14 [109], LombardiMB13 [407], BonfiettiLBM12 [108], BonfiettiLBM11 [107], LombardiBMB11 [400], BeniniLMR11 [90], LombardiMRB10 [408], RuggieroBBMA09 [525], BeniniLMR08 [89], BeniniBGM06 [88] |
| Philippe Laborie | 12 | 513 | LunardiBLRV20 [413], LaborieRSV18 [372], Laborie18a [371], MelgarejoLS15 [11], VilimLS15 [621], Laborie09 [370], BidotVLB09 [94], BaptisteLPN06 [47], NeronABCDD06 [481], GodardLN05 [245], Laborie03 [369], FocacciLN00 [215] |
| Philippe Baptiste | 11 | 403 | BaptisteB18 [46], Baptiste09 [45], BaptisteLPN06 [47], NeronABCDD06 [481], ArtiouchineB05 [34], Baptiste02 [44], BaptistePN01 [50], BaptisteP00 [49], PapaB98 [492], BaptisteP97 [48], PapeB97 [491] |
| Roman Barták | 11 | 88 | SvancaraB22 [569], JelinekB16 [325], BartakV15 [59], Bartak14 [55], BartakS11 [57], BartakCS10 [56], BartakSR10 [58], VilimBC05 [620], VilimBC04 [619], Bartak02 [54], Bartak02a [53] |

## 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

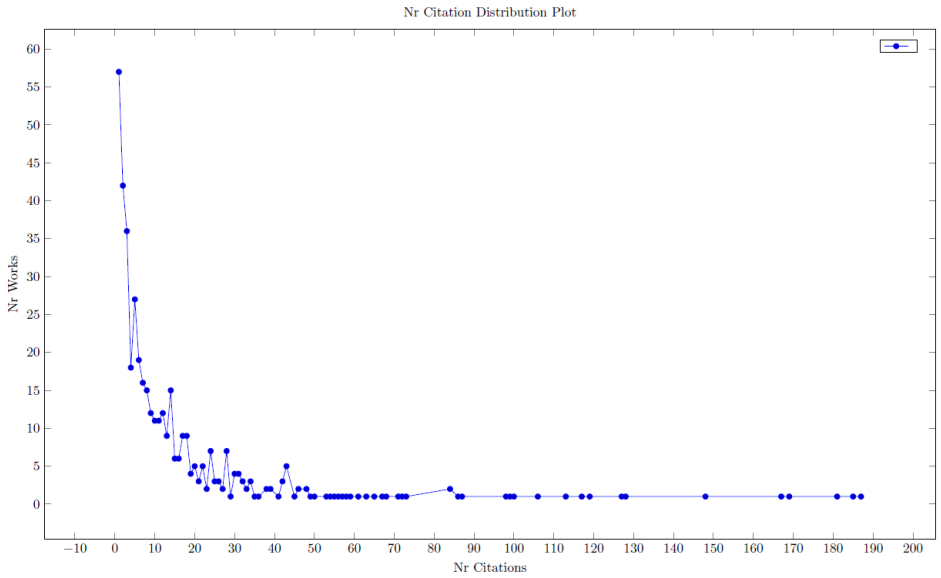
Table 9: Works from bibtex (Total 30)

| 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 |
| KuB16 KuB16 | 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. Lemaître, 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. Lu, 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

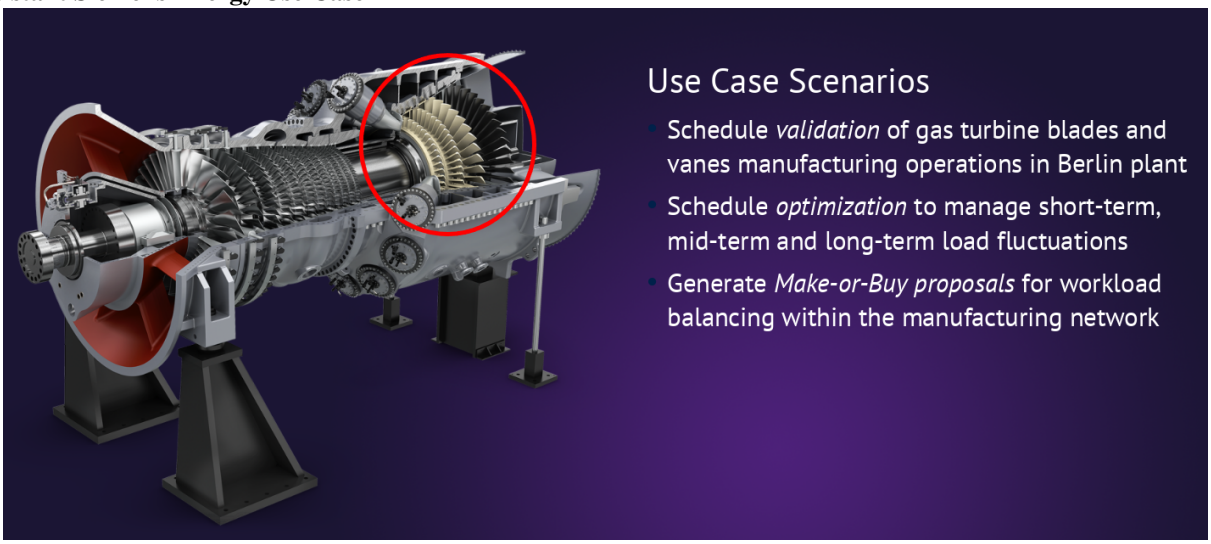
- Selection of other problem types
  - Only summary slide shown

# 2 ASSISTANT SE Use Case

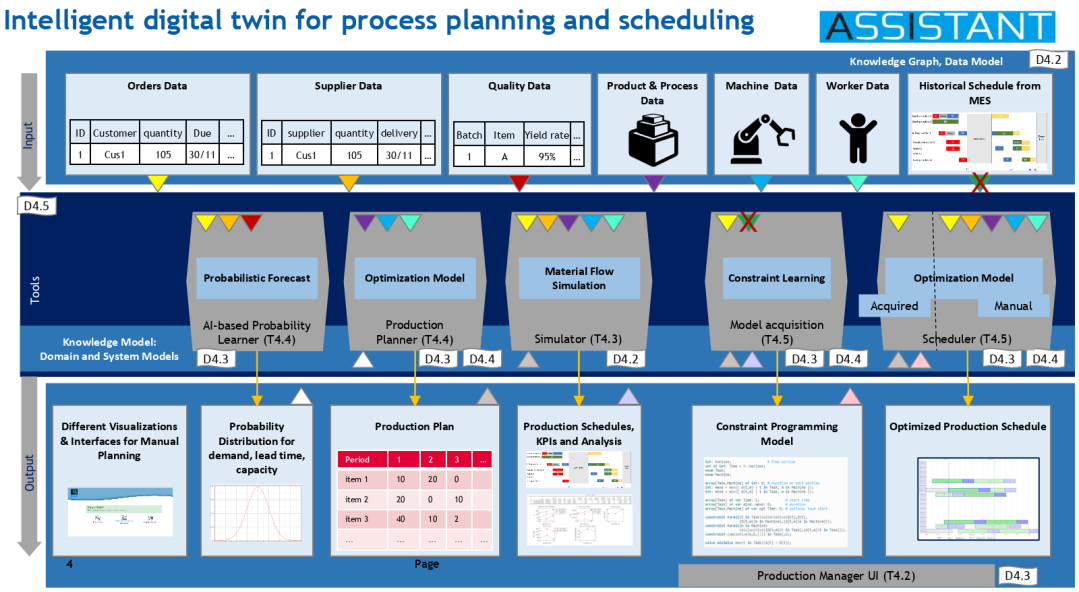
**An Industrial Example**

- 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

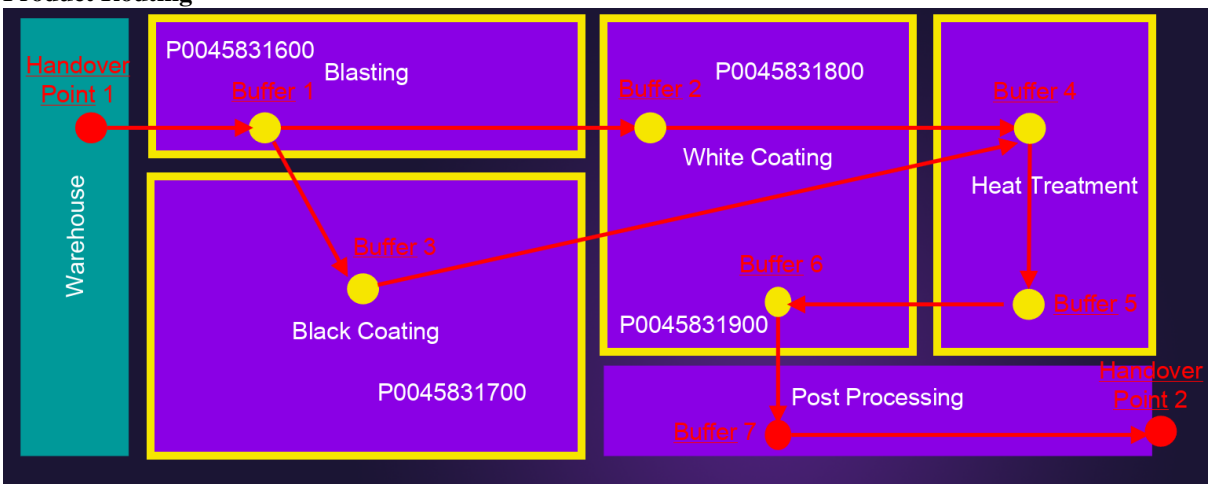
**Assistant Siemens Energy Use Case**




**Digital Twin**




**SE Product Routing**




**Datasets**

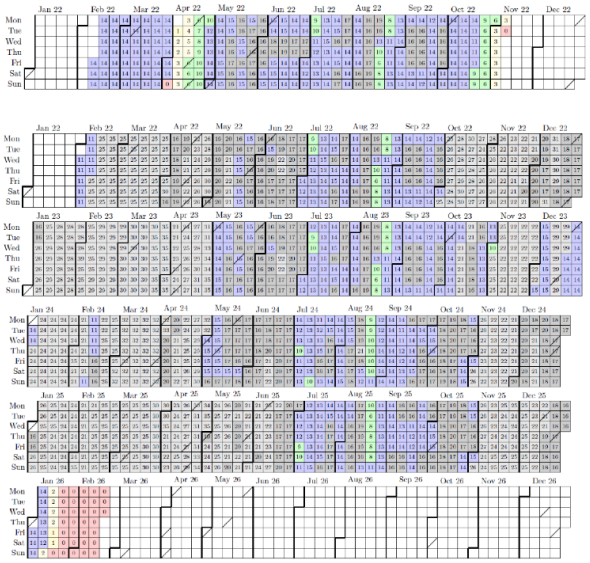
## Full Scale Datasets

Berlin06: 96 orders, 9 months horizon, previous review

Berlin07: 450 orders, 4 years horizon

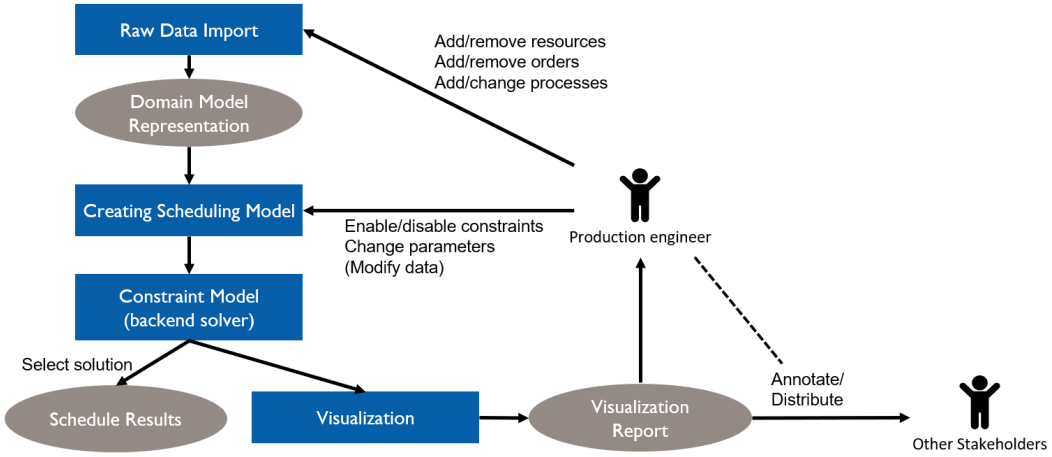
Berlin08: 559 orders, Christmas gap added

Berlin08a: 670 orders, filling gaps



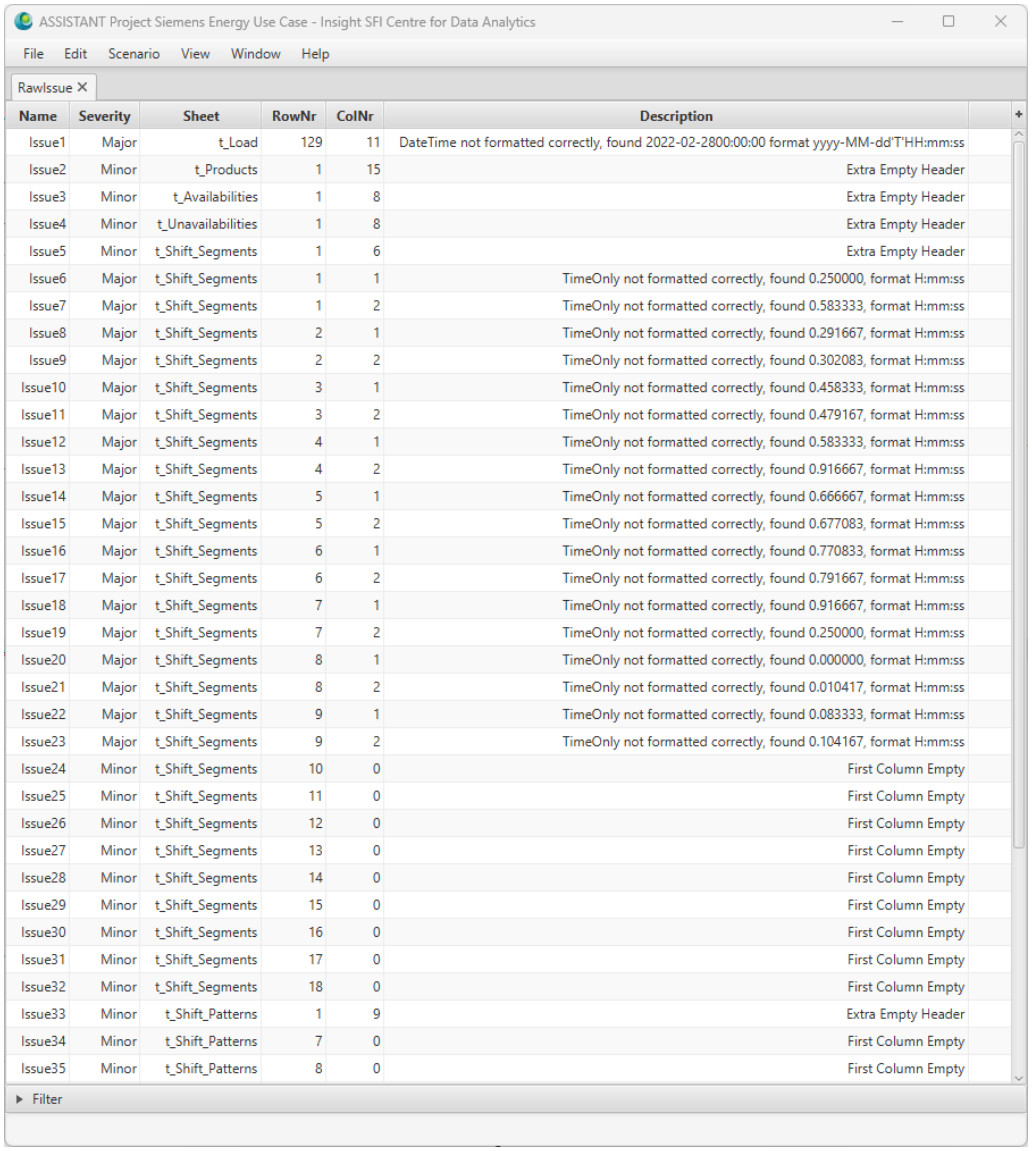
Value in cell indicates active orders
Yellow and red colors indicate low order volume

### Optimizer High Level Structure




### Raw Data - Manual Data Entry Causes Problems

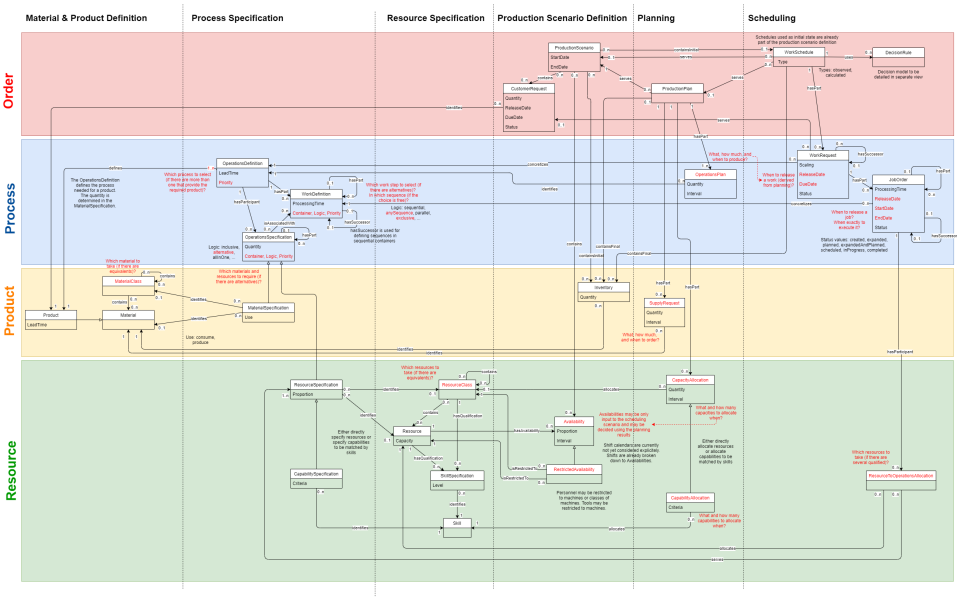
- Raw data come from spreadsheet
  - 20 tabs
- Excel is a particularly bad input data format
- Realistic, not real data
- Created by hand/automatically from existing test scenarios
- Series of files Berlin01 - Berlin05 were too inconsistent to run
- Berlin06 still contains some errors
- Optimizer explains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



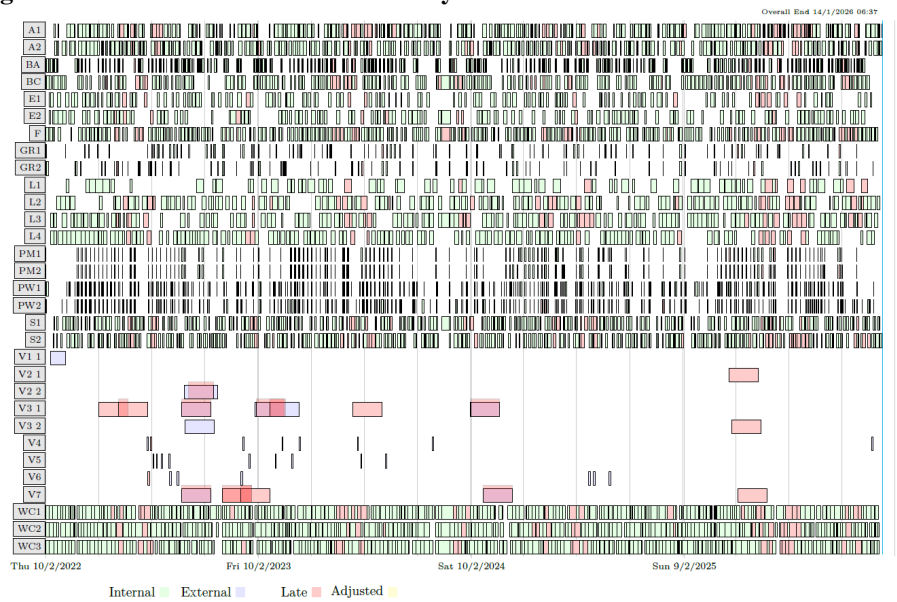

| Name | Severity | Sheet | RowNr | ColNr | Description |
|---|---|---|---|---|---|
| Issue1 | Major | t_Load | 129 | 11 | DateTime not formatted correctly, found 2022-02-2800:00:00 format yyyy-MM-dd'T'HH:mm:ss |
| Issue2 | Minor | t_Products | 1 | 15 | Extra Empty Header |
| Issue3 | Minor | t_Availabilities | 1 | 8 | Extra Empty Header |
| Issue4 | Minor | t_Unavailabilities | 1 | 8 | Extra Empty Header |
| Issue5 | Minor | t_Shift_Segments | 1 | 6 | Extra Empty Header |
| Issue6 | Major | t_Shift_Segments | 1 | 1 | TimeOnly not formatted correctly, found 0.250000, format H:mm:ss |
| Issue7 | Major | t_Shift_Segments | 1 | 2 | TimeOnly not formatted correctly, found 0.583333, format H:mm:ss |
| Issue8 | Major | t_Shift_Segments | 2 | 1 | TimeOnly not formatted correctly, found 0.291667, format H:mm:ss |
| Issue9 | Major | t_Shift_Segments | 2 | 2 | TimeOnly not formatted correctly, found 0.302083, format H:mm:ss |
| Issue10 | Major | t_Shift_Segments | 3 | 1 | TimeOnly not formatted correctly, found 0.458333, format H:mm:ss |
| Issue11 | Major | t_Shift_Segments | 3 | 2 | TimeOnly not formatted correctly, found 0.479167, format H:mm:ss |
| Issue12 | Major | t_Shift_Segments | 4 | 1 | TimeOnly not formatted correctly, found 0.583333, format H:mm:ss |
| Issue13 | Major | t_Shift_Segments | 4 | 2 | TimeOnly not formatted correctly, found 0.916667, format H:mm:ss |
| Issue14 | Major | t_Shift_Segments | 5 | 1 | TimeOnly not formatted correctly, found 0.666667, format H:mm:ss |
| Issue15 | Major | t_Shift_Segments | 5 | 2 | TimeOnly not formatted correctly, found 0.677083, format H:mm:ss |
| Issue16 | Major | t_Shift_Segments | 6 | 1 | TimeOnly not formatted correctly, found 0.770833, format H:mm:ss |
| Issue17 | Major | t_Shift_Segments | 6 | 2 | TimeOnly not formatted correctly, found 0.791667, format H:mm:ss |
| Issue18 | Major | t_Shift_Segments | 7 | 1 | TimeOnly not formatted correctly, found 0.916667, format H:mm:ss |
| Issue19 | Major | t_Shift_Segments | 7 | 2 | TimeOnly not formatted correctly, found 0.250000, format H:mm:ss |
| Issue20 | Major | t_Shift_Segments | 8 | 1 | TimeOnly not formatted correctly, found 0.000000, format H:mm:ss |
| Issue21 | Major | t_Shift_Segments | 8 | 2 | TimeOnly not formatted correctly, found 0.010417, format H:mm:ss |
| Issue22 | Major | t_Shift_Segments | 9 | 1 | TimeOnly not formatted correctly, found 0.083333, format H:mm:ss |
| Issue23 | Major | t_Shift_Segments | 9 | 2 | TimeOnly not formatted correctly, found 0.104167, format H:mm:ss |
| Issue24 | Minor | t_Shift_Segments | 10 | 0 | First Column Empty |
| Issue25 | Minor | t_Shift_Segments | 11 | 0 | First Column Empty |
| Issue26 | Minor | t_Shift_Segments | 12 | 0 | First Column Empty |
| Issue27 | Minor | t_Shift_Segments | 13 | 0 | First Column Empty |
| Issue28 | Minor | t_Shift_Segments | 14 | 0 | First Column Empty |
| Issue29 | Minor | t_Shift_Segments | 15 | 0 | First Column Empty |
| Issue30 | Minor | t_Shift_Segments | 16 | 0 | First Column Empty |
| Issue31 | Minor | t_Shift_Segments | 17 | 0 | First Column Empty |
| Issue32 | Minor | t_Shift_Segments | 18 | 0 | First Column Empty |
| Issue33 | Minor | t_Shift_Patterns | 1 | 9 | Extra Empty Header |
| Issue34 | Minor | t_Shift_Patterns | 7 | 0 | First Column Empty |
| Issue35 | Minor | t_Shift_Patterns | 8 | 0 | First Column Empty |



**Domain Model - Knowledge Graph**




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



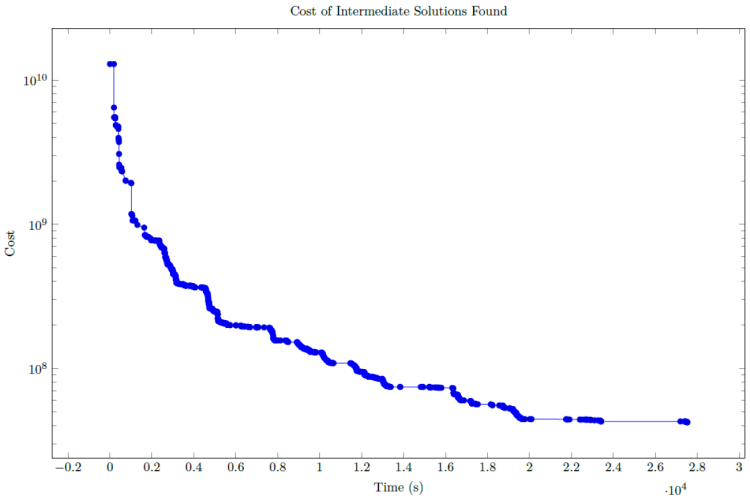

## Implementation

- 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

# 3 Outpatient Waitlist Management

### Joint work with...

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

## 3.1 Introduction

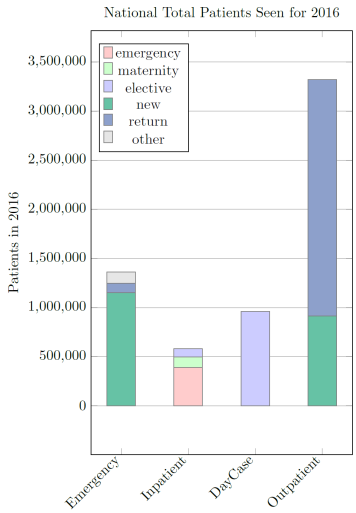
### Real-World Problem

- 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

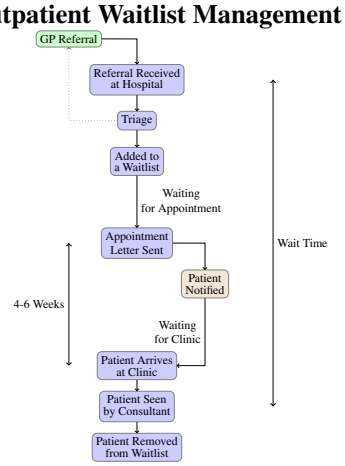
**Rapid access** seen within 14 days

**Urgent** seen within 28 days

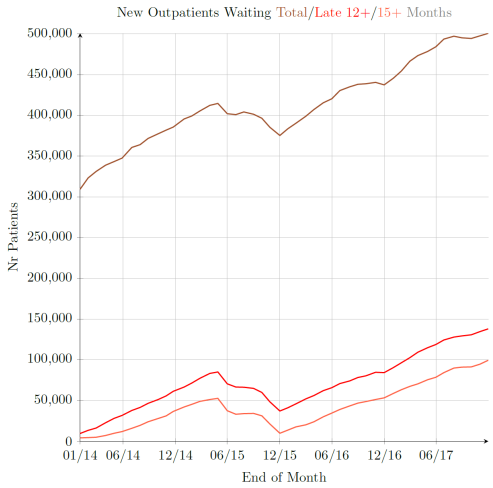
**Soon** seen within 3 months

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

### Outpatient Waitlist Management Process (Simplified)

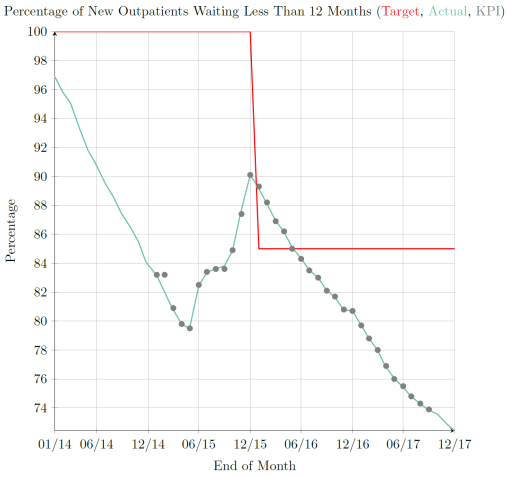


### The Bad News




Data: NTPF

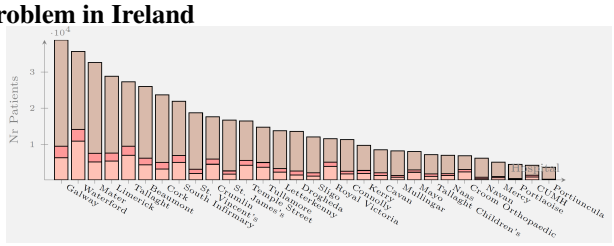
### KPI: Waiting Time Percentage



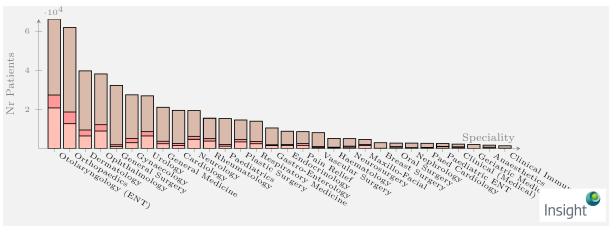

Data: HSE

### A Near Universal Problem in Ireland

By Hospital




By Speciality




## 3.2 Solution Approach

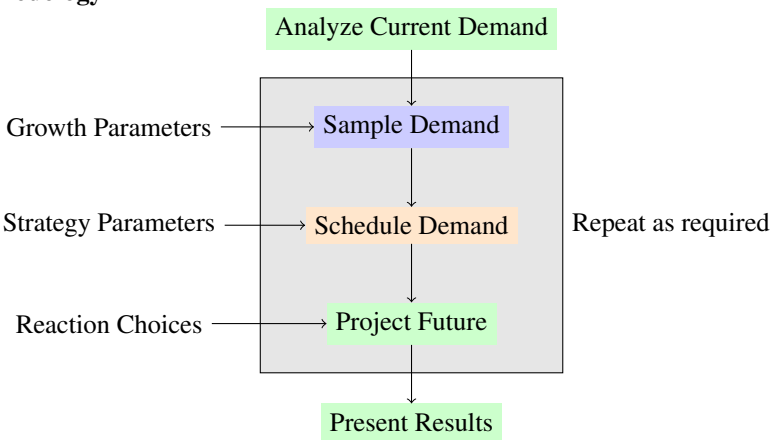
### Our Brief

- 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**

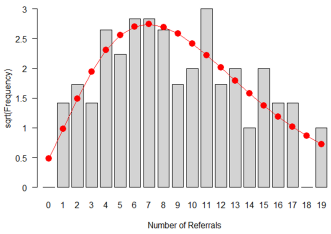
- We have to give "routine" appointment before knowing "urgent" demand
- There is limited capacity
- No overtime allowed (Croke Park agreement)
- How much capacity to set aside for urgent cases?
- How much overbooking is possible?

**Methodology**

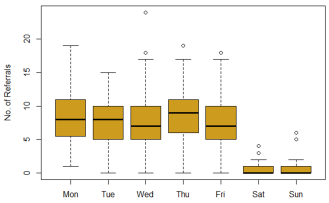



**Demand Data (Not Public)**

Received Per Day

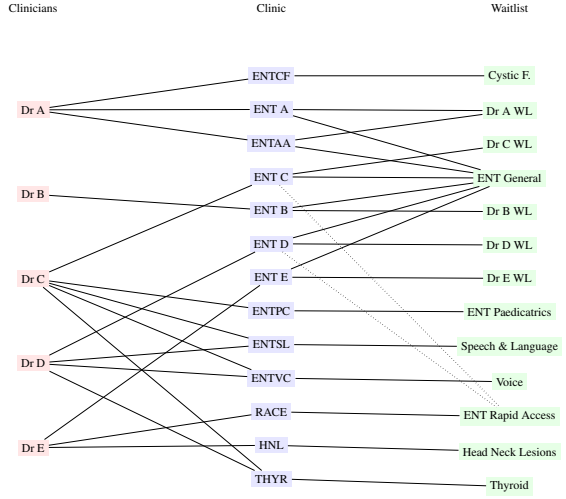



Received Per Day of Week

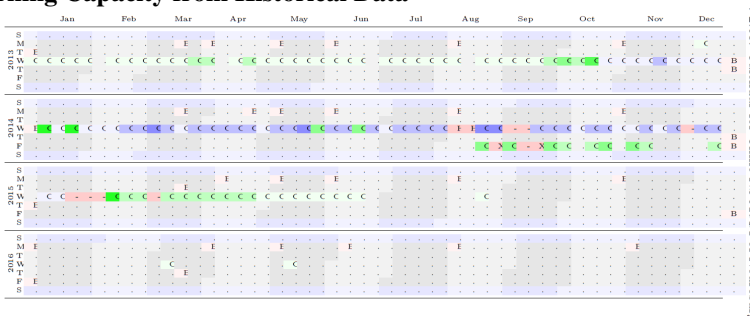



- Fitting distributions
  - Poisson, not good fit
  - Negative Binomial
- Limited Seasonality (unlike Emergency Department)

## Waitlist/Clinic Model




## Learning Capacity from Historical Data

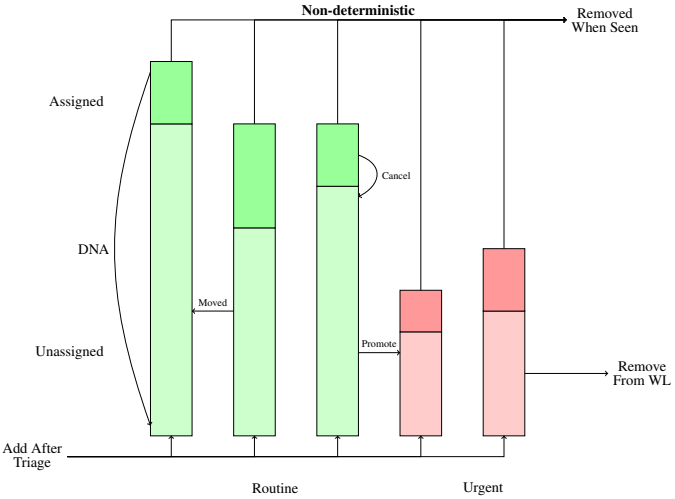



- Repeat frequency
- Capacity
- Cancellation frequency
- Replacement clinics

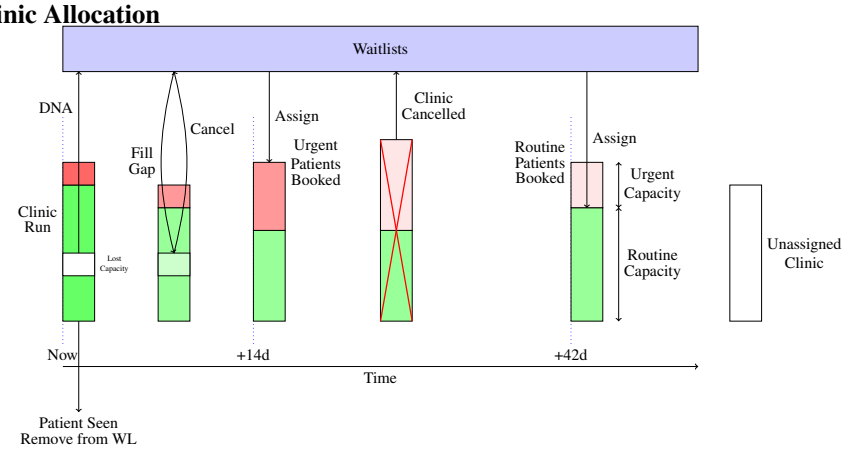
## Optimization Problem

- 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

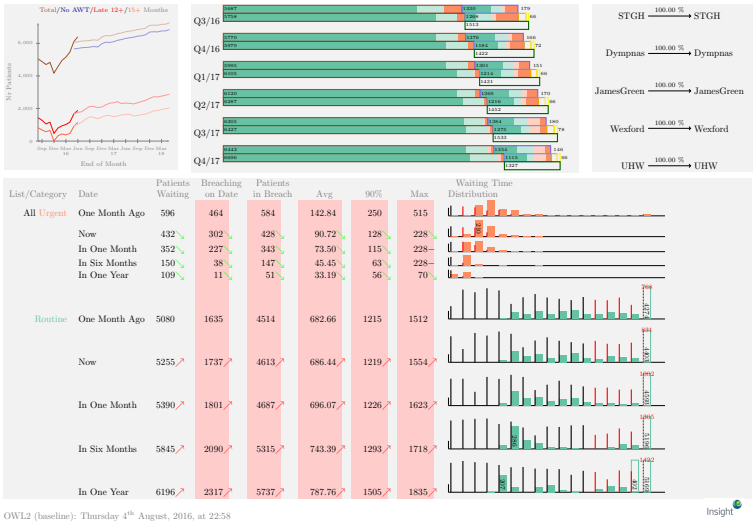



### Clinic Allocation

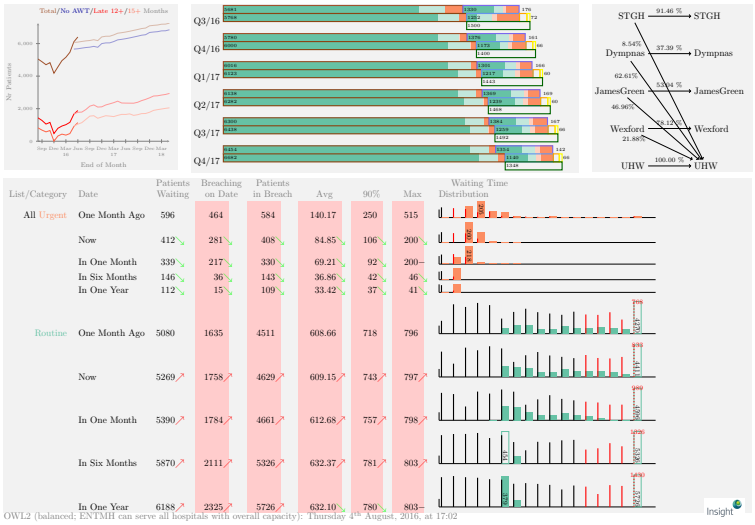



## 3.3 Results

### Baseline Analysis, Management View



## Scenario: Balance Patients Between Hospitals

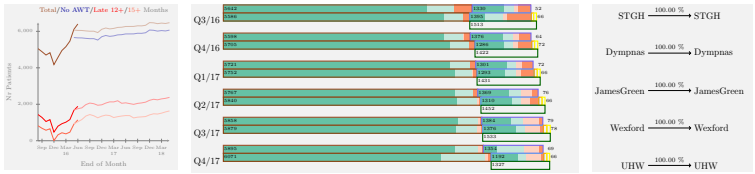



| List/Category | Date | Patients Waiting | Breaching on Date | Patients in Breach | Avg | 90% | Max | Waiting Time Distribution |
|---|---|---|---|---|---|---|---|---|
| All Urgent | One Month Ago | 596 | 464 | 584 | 140.17 | 250 | 515 | |
| | Now | 412 ↘ | 281 ↘ | 408 ↘ | 84.85 ↘ | 106 ↘ | 200 ↘ | |
| | 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

Insight

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

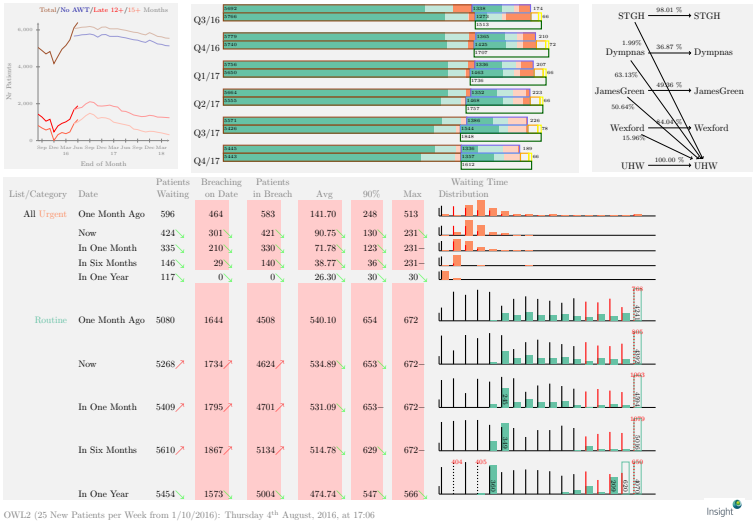



| List/Category | Date | Patients Waiting | Breaching on Date | Patients in Breach | Avg | 90% | Max | Waiting Time Distribution |
|---|---|---|---|---|---|---|---|---|
| All Urgent | One Month Ago | 596 | 464 | 584 | 142.64 | 250 | 515 | |
| | Now | 404 ↘ | 300 ↘ | 401 ↘ | 91.83 ↘ | 128 ↘ | 228 ↘ | |
| | 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 ↗ | |

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

Insight

## Scenario: Add Capacity




## 3.4 Summary

**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

# 4 Elevator Maintenance Planning and Scheduling

**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

## 4.1 Introduction

**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?

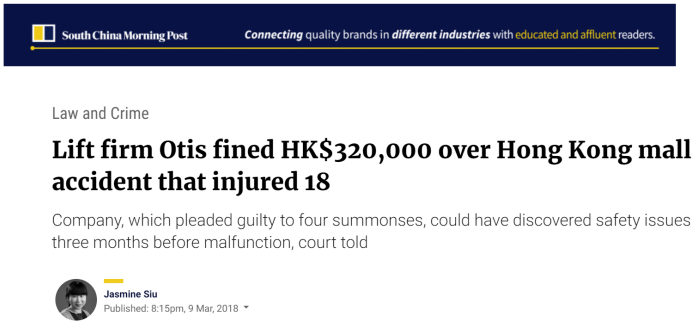
**Research Challenge**

- 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

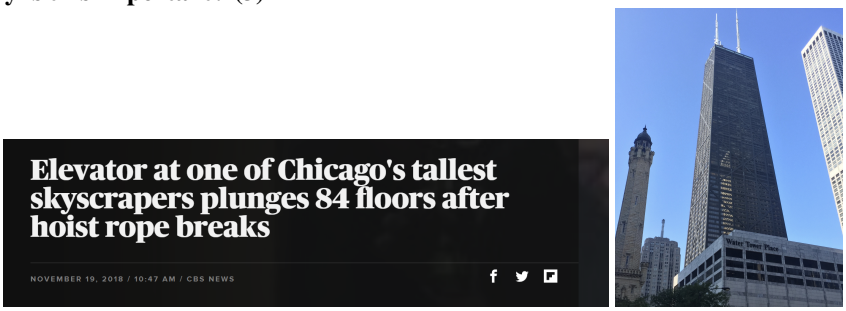
**Why is this important? (1)**




**Why is this important? (2)**


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

## 4.2 Our Contribution

### High-level View

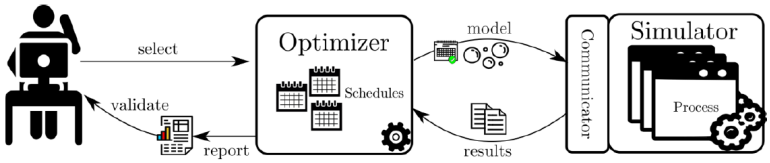


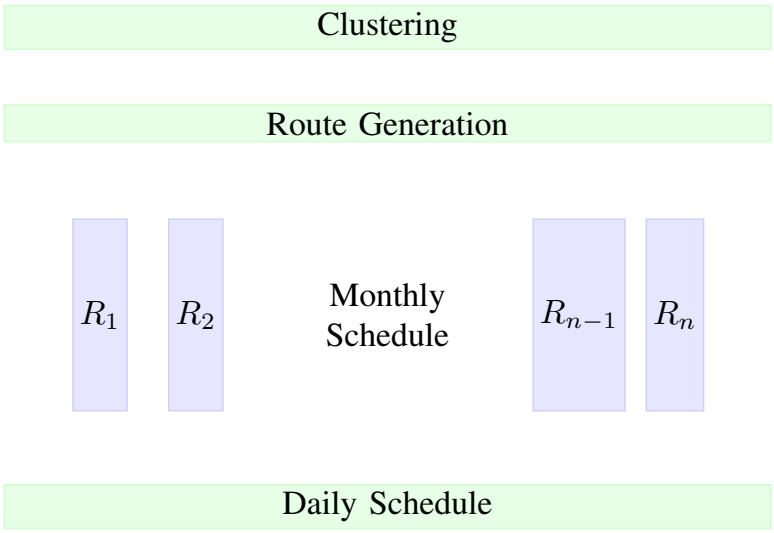

Figure 1 High level overview of the framework

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

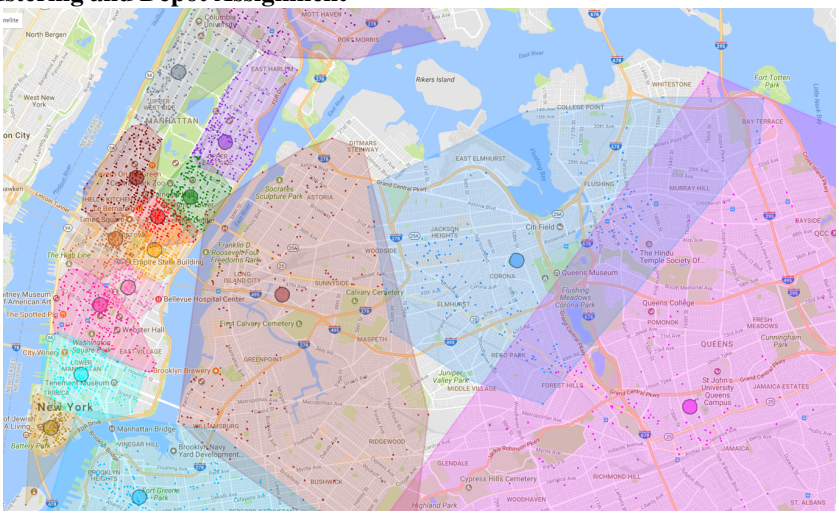
### Optimizer Design

- 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

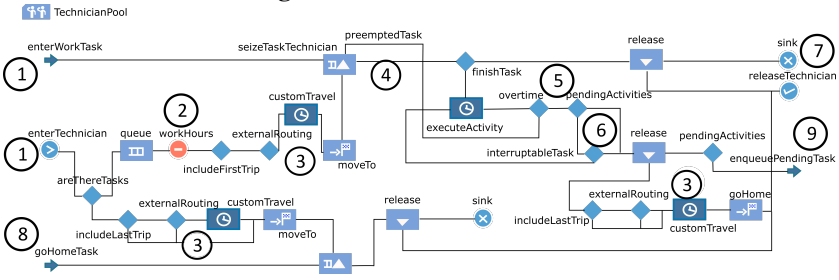
**Clustering** Connected components on generated graph

**Routing** Which places to visit in one trip

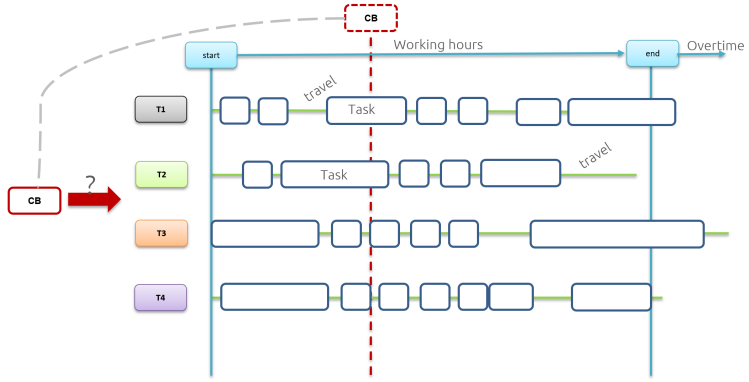
- Core MIP Model
- Iterative MIP inside Clustering
- Two stage grouping of locations to reduce expected travel
- Local Search

**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?

## 4.3 Evaluation

### 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

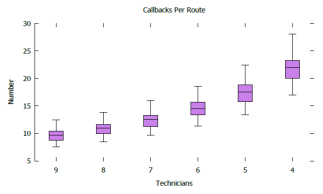



Figure 6 Callbacks per route (technician)

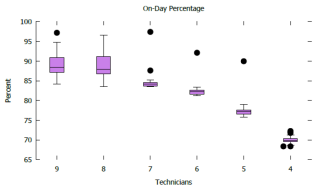



Figure 7 Percentage of tasks performed per tasks

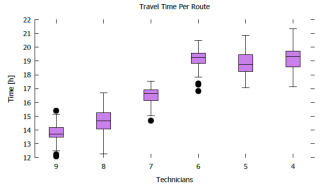



Figure 9 Travel time per technician

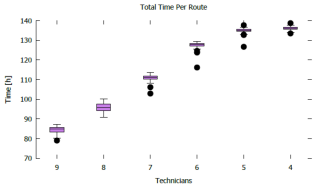
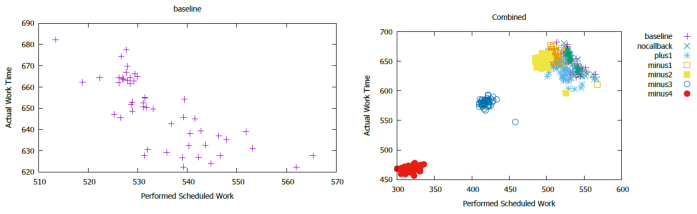



Figure 8 Total time per technician

### 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

## 4.4 Challenges

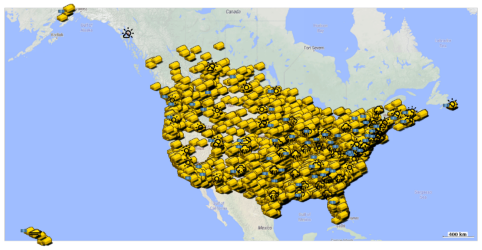
### Challenges: Data

- 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

# 5 Other Applications

**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

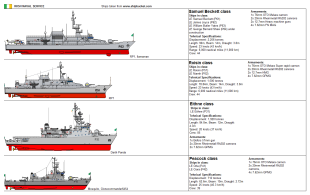
**Boliden Tara Mines Dewatering**

- 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**

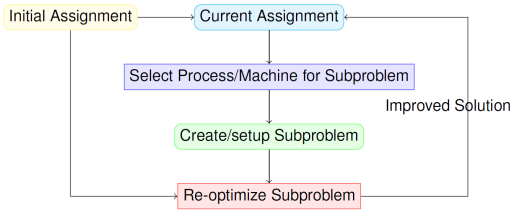
- Real-World Problem
  - Change time table during period of teaching capacity increase
  - Previous schedule no longer feasible
  - Multiple courses share same lab space (dental chairs) at the same time
  - Hard capacity limits on available resources and time slots
- Status
  - Used by dental school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



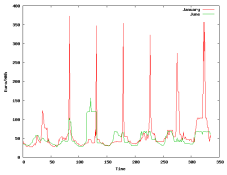
- Real-World Problem
  - Decide which ships are performing which type of duty over the year
  - Budget limitations on total time at sea
  - Fair share of work across fleet
  - Fixed maintenance periods for certain ships
  - Special events (flotilla exercises, detached duty)
- Status
  - Prototype results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



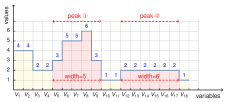

- Real-World Problem
  - Move virtual machines between servers in a data centre
  - Balance/concentrate workload on multiple resource types
  - Extend to multiple data centres across world
- Status
  - 2nd place in Google Roadef/Euro Challenge 2012
  - Multiple papers
- Research Challenges
  - Reassignment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



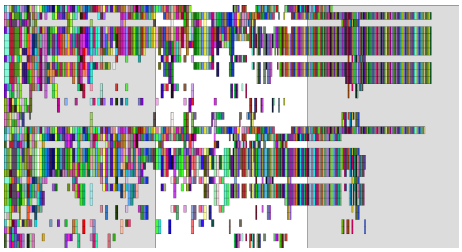
- Real-World Problem
  - How do time-variable electricity prices affect scheduling of use
  - Uncertainty of prices, sudden peak prices common in Ireland
  - In most cases, we have to commit to production before price is known
  - Deal with risk/possible rewards
- Status
  - Multiple papers
  - Continued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



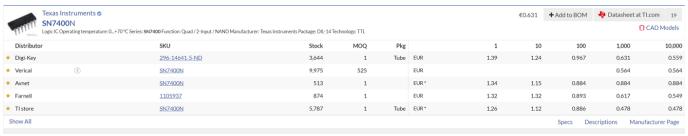
- Real-World Problem
  - Unit Commitment Model for electricity supply
  - Decide which units to run when to satisfy demand/minimize cost
  - Change of production for different units is limited over time
  - Very error-prone integration into global model
- Status
  - Joint work with IMT-Atlantique, EDF 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**



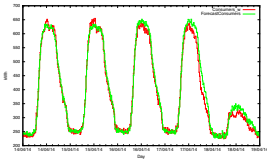
- Real-World Problem
  - Core optical network design
  - Different from traditional IP network design
  - Define paths from source to sink
  - Use multiple frequency (light) bands over same fibre
- Status
  - paper ICTAI 2014
- Research Challenges
  - Modelling Choices
  - Amount of propagation achieved
  - 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

# 6 Summary

**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