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Scheduling Examples for Constraint Acquisition

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Overview

- Why scheduling is a good field for Constraint Acquisition (CA)
- Present what scheduling problems looks like
- From simple to complex
- Give links to data in literature
- Show some realistic examples
- Focus on data, not algorithms

Why Scheduling?

- This is the most successful application area for Constraint Programming (CP)
- Huge variety of different problem types and sub-types
- Often involves optimization of some objective(s)
- CP works best when there are many side constraints
  - Easy to add to a model
- There is a lot of literature
- Scheduling is important for many users

Challenges

- Nearly always instances of different sizes
- Underlying problem is constantly evolving
  - New/deleted products, processes, machines
  - You need snapshot of relevant background data to reproduce results
- Nobody is interested in resolving previously solved instances
  - Unless you find better objective value
- There is rarely more than one solution kept for each instance
- Typically no non-solutions are produced and/or stored
- You may have different plans based on compromises between objectives/stakeholders

Challenges (II)

- New instances are constantly added (every day)
  - We need to generate solutions for these unseen instances
- Big difference between planned schedule and actual, observed schedule
  - Machine break-downs
  - Quality issues, rework
  - Rush-orders, cancellations
  - Impact of (lack of) component stock
- Don’t do as I do, do as I say
  - You don’t want to learn the bad ways of fire-fighting
  - Hope that the original plan is stored, as well as the actual production data

Existing Literature

- Methods to Learn Abstract Scheduling Models. Carchrae, Beck, Freuder. CP 2005. [9]
  - Suggests backdoor based approach to project scheduling
- Learning Scheduling Models from Event Data. Senderovich, Booth, Beck. ICAPS 2019. [40]
  - Learning models from traces of execution of actual schedules
- Guided Bottom-Up Interactive Constraint Acquisition. Tsouros, Berden, Guns. CP 2023. [42]
  - Example of smallish job-shop problem
- Boolean-Arithmetic Equations: Acquisition and Uses. Gindullin, Beldiceanu, Cheukam-Ngouonou, Douence, Quimper. CPAIOR 2023. [18]
  - Learning formulas from tables

My Interest

- "Passive" Constraint Acquisition
  - Learn from positive (negative) examples
  - Few (one) solutions per instances, many instances
- Search for transferable model
  - Learn model from samples, apply to unseen instances
- Deal with large number of hidden variables
  - Stored results only show actionable decisions
- No membership queries for humans
  - Ask more meaningful questions: Can you interrupt execution of a task on this machine?
  - Automated oracles can only answer full queries

Table of Contents

Examples from Books on CP

- Can we acquire the models of scheduling problems in books on CP?
- Which books? There are books?

Books on CP

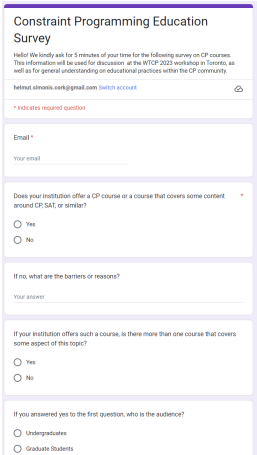
Author	Title	Year	Pages	Language	CP System	Exercises
P Van Hentenryck	Constraint satisfaction in logic programming[20]	1989	224	English	CHIP[12]	-
F. Fages	Programmation logique par contraintes[13]	1996	192	French	GNU Prolog	yes
K. Marriott, P. Stuckey	Programming with Constraints[32]	1998	467	English	CLP(R)[27]	yes
P Van Hentenryck	The OPL Optimization Programming Language[21]	1999	254	English	OPL[22]	???
J. Hooker	Logic-Based Methods for Optimization[24]	2000	495	English	-	no
K. Apt	Principles of Constraint Programming[2]	2003	407	English	-	yes
R. Dechter	Constraint processing[11]	2003	481	English	-	???
T. Frühwirth, S. Abdennadher	Essentials of constraint programming[14]	2003	156	English	CHR	no
K. Apt, M. Wallace	Constraint Logic Programming using ECLiPSe [3]	2007	329	English	ECLiPSe[39]	yes
J. Hooker	Integrated Methods for Optimization[25]	2007	486	English	-	yes
P. Hofstedt, A. Wolf	Einführung in die Constraint-Programmierung[23]	2007	388	German	TURTLE[19] firstcs[44]	yes

Books on CP (II)

Author	Title	Year	Pages	Language	CP System	Exercises
D. Poole, A. Mackworth	Artificial Intelligence - Foundations of Computational Agents[35]	2010	900 (CSP ???)	English	-	yes
C. Lecoutre	Constraint Networks: Targeting Simplicity for Techniques and Algorithms[30]	2013	320	English	???	???
A. Niederlinski	A Gentle Guide to Constraint Logic Programming via ECLiPSe[34]	2014	509	English	ECLiPSe[39]	yes
E. Tsang	Foundations of Constraint Satisfaction: The Classic Text[41]	2014	444	English	???	???
N. Zhou, H. Kjellerstrand, J. Fruhman	Constraint Solving and Planning with Picat[46]	2015	140	English	Picat[45]	yes
E. Bourreau, M. Gondran, P. Lacomme, M. Vinot	De la programmation linéaire à la programmation par contraintes[7]	2019	348	French	Gusek CPLEX GLPK Choco[37]	no
E. Bourreau, M. Gondran, P. Lacomme, M. Vinot	Programmation par Contraintes[8]	2020	232	French	Choco[37]	no
S. Russell, P. Norvig	Artificial Intelligence: A Modern Approach (4th Edition)[38]	2020	1115 (CSP 28)	English	-	no
M. Wallace	Building Decision Support Systems - using MiniZinc[43]	2020	224	English	MiniZinc[33]	yes

Source: Workshop on Teaching Constraint Programming, Santanam, Simonis, 2023

- Tejas and myself are working on overview paper based on workshop
- Exists in draft form, if you are interested
- If you are teaching a CP course, please fill in
  - `https://forms.gle/v54HUsbSXcyHmfME9`
  - or contact us!



Constraint Programming Education Survey

Hello! We kindly ask for 5 minutes of your time for the following survey on CP courses. This information will be used for discussion at the WTCP 2023 workshop in Toronto, as well as for general understanding on educational practices within the CP community.

helmut.simonis.cork@gmail.com Switch account

* Indicates required question

Email *

Your email

Does your institution offer a CP course or a course that covers some content around CP, SAT, or similar? *

Yes

No

If no, what are the barriers or reasons?

Your answer

If your institution offers such a course, is there more than one course that covers some aspect of this topic?

Yes

No

If you answered yes to the first question, who is the audience?

Undergraduates

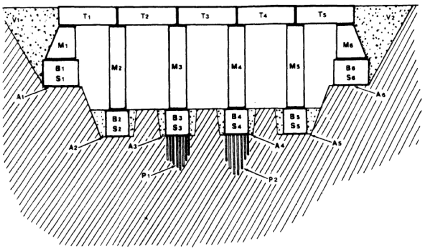
Graduate Students

Some Example Scheduling Problems

- Importance of data to acquire problem
- Constraint structure given as part of data, or implicit as part of problem structure
- Very often: data hardcoded in program
  - It saves space...
  - We should not teach this

Bridge Scheduling Problem (Van Hentenryck 1989 [20])

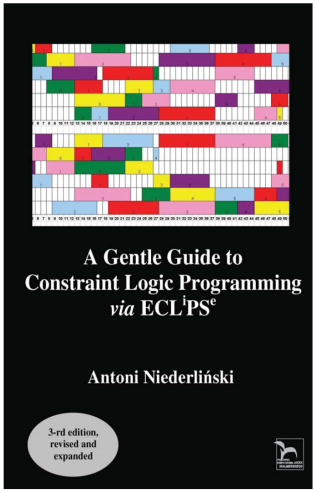
- First scheduling problem with CHIP
- Based on PhD thesis of Bartusch
- Disjunctive Scheduling (RCPSP)
- Different types of temporal relations
- Minimize makespan



N	Name	description	duration	resource
1	PA	beginning of project	0	-
2	A1	excavation (abutment 1)	4	excavator
3	A2	excavation (pillar 1)	2	excavator
4	A3	excavation (pillar 2)	2	excavator
5	A4	excavation (pillar 3)	2	excavator
6	A5	excavation (pillar 4)	2	excavator
7	A6	excavation (abutment 2)	5	excavator
8	P1	foundation piles 2	20	pile-driver
9	P2	foundation piles 3	13	pile-driver
10	UE	erection of temporary housing	10	-
11	S1	formwork (abutment 1)	8	carpentry
12	S2	formwork (pillar 1)	4	carpentry
13	S3	formwork (pillar 2)	4	carpentry
14	S4	formwork (pillar 3)	4	carpentry
15	S5	formwork (pillar 4)	4	carpentry
16	S6	formwork (abutment 2)	10	carpentry
17	B1	concrete foundation (abutment 1)	1	concrete-mixer
18	B2	concrete foundation (pillar 1)	1	concrete-mixer
19	B3	concrete foundation (pillar 2)	1	concrete-mixer
20	B4	concrete foundation (pillar 3)	1	concrete-mixer
21	B5	concrete foundation (pillar 4)	1	concrete-mixer
22	B6	concrete foundation (abutment 2)	1	concrete-mixer
23	AB1	concrete setting time (abutment 1)	1	-
24	AB2	concrete setting time (pillar 1)	1	-
25	AB3	concrete setting time (pillar 2)	1	-
26	AB4	concrete setting time (pillar 3)	1	-
27	AB5	concrete setting time (pillar 4)	1	-
28	AB6	concrete setting time (abutment 2)	1	-
29	M1	masonry work (abutment 1)	16	bricklaying
30	M2	masonry work (pillar 1)	8	bricklaying
31	M3	masonry work (pillar 2)	8	bricklaying
32	M4	masonry work (pillar 3)	8	bricklaying
33	M5	masonry work (pillar 4)	8	bricklaying
34	M6	masonry work (abutment 2)	20	bricklaying
35	L	delivery of the preformed bearers	2	crane
36	T1	positioning (preformed bearer 1)	12	crane
37	T2	positioning (preformed bearer 2)	12	crane
38	T3	positioning (preformed bearer 3)	12	crane
39	T4	positioning (preformed bearer 4)	12	crane
40	T5	positioning (preformed bearer 5)	12	crane
41	UA	removal of the temporary housing	10	-
42	V1	filling 1	15	caterpillar
43	V2	filling 2	10	caterpillar
44	K1	point 1 of cost function	0	-
45	K2	point 2 of cost function	0	-
46	PE	end of project	0	-

A Gentle Guide to Constraint Logic Programming (Niederlinski 2014 [34])

- Discusses many scheduling examples
- Most are open-coded, no separation of program and data
- ECLiPSe code given
- Result visualizations given



Ship Loading Example

```
/*9*/   LS   :: 1..400,
/*10*/  LD :: 1..40,
/*11*/  LR :: 1..12,
/*12*/  End :: 1..400,
/*13*/  Limit :: 1..12,

/*14*/  cumulative(LS,LD,[R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,
            R12,R13,R14,R15,R16,R17,R18,R19,R20,R21,R22,
                R23,R24,R25,R26,R27,R28,R29,R30,R31,R32,R33,R34],
                    LF,Limit),

/*15*/  S1 + D1 #=< S2,
/*16*/  S1 + D1 #=< S4,
/*17*/  S2 + D2 #=< S3,
/*18*/  S3 + D3 #=< S5,
/*19*/  S3 + D3 #=< S7,
/*20*/  S4 + D4 #=< S5,
/*21*/  S5 + D5 #=< S6,
/*22*/  S6 + D6 #=< S8,
/*23*/  S7 + D7 #=< S8,
/*24*/  S8 + D8 #=< S9,
/*25*/  S9 + D9 #=< S10,
/*26*/  S9 + D9 #=< S14,
/*27*/  S10 + D10 #=< S11,
/*28*/  S10 + D10 #=< S12,
/*29*/  S11 + D11 #=< S13,
/*30*/  S12 + D12 #=< S13,
/*31*/  S13 + D13 #=< S15,
/*32*/  S13 + D13 #=< S16,
/*33*/  S14 + D14 #=< S15,
/*34*/  S15 + D15 #=< S18,
/*35*/  S16 + D16 #=< S17,
/*36*/  S17 + D17 #=< S18,
/*37*/  S18 + D18 #=< S19,
/*38*/  S18 + D18 #=< S20,
```

Task	Man-hours	Next task
1	12	2, 4
2	16	3
3	12	5, 7
4	24	5
5	25	6
6	10	8
7	12	8
8	12	9
9	12	10, 14
10	16	11, 12
11	12	13
12	10	13
13	4	15,16
14	15	15
15	6	18
16	9	17
17	12	18
18	14	19, 20, 21
19	4	23
20	4	23
21	4	22
22	8	23
23	28	24
24	40	25
25	16	26,30,31,32
26	3	27
27	3	28
28	12	29
29	8	end
30	9	28
31	6	28
32	3	28
33	6	34
34	6	end

Job-Shop (Wallace, 2020 [43])

```
int: n_machines;
int: n_jobs;
int: n_tasks = n_machines;
set of int: jobs = 1..n_jobs;
set of int: tasks = 1..n_tasks;
set of int: machines = 1..n_machines ;
array [jobs, tasks] of machines: jt_machine;
array [jobs, tasks] of int: jt_duration;
int: max_end = 1050 ;

array [jobs, tasks] of var 0.. max_end: jt_start;
var 0..max_end: t_end ;

constraint
forall ( j in jobs, k in 1..(n_tasks - 1) ) (
  jt_start[j, k] + jt_duration[j, k] <=
    jt_start[j, k + 1]
);
include "disjunctive.mzn" ;
constraint
forall(m in machines)
  (disjunctive(
    [jt_start[j,t]|j in jobs,t in tasks where jt_machine[j,t]=m],
    [jt_duration[j,t]|j in jobs, t in tasks where jt_machine[j,t]=m])
) ;

solve minimize t_end ;
```

```
n_jobs = 10;
n_machines = 10;
jt_machine = array2d(jobs, tasks,
[ 0, 1, 2, 3, 4, 5, 6, 7, 8, 9,
0, 2, 4, 9, 3, 1, 6, 5, 7, 8,
1, 0, 3, 2, 8, 5, 7, 6, 9, 4,
1, 2, 0, 4, 6, 8, 7, 3, 9, 5,
2, 0, 1, 5, 3, 4, 8, 7, 9, 6,
2, 1, 5, 3, 8, 9, 0, 6, 4, 7,
1, 0, 3, 2, 6, 5, 9, 8, 7, 4,
2, 0, 1, 5, 4, 6, 8, 9, 7, 3,
0, 1, 3, 5, 2, 9, 6, 7, 4, 8,
1, 0, 2, 6, 8, 9, 5, 3, 4, 7 ]);
jt_duration = array2d(jobs, tasks, [
29, 78, 9, 36, 49, 11, 62, 56, 44, 21,
43, 90, 75, 11, 69, 28, 46, 46, 72, 30,
91, 85, 39, 74, 90, 10, 12, 89, 45, 33,
81, 95, 71, 99, 9, 52, 85, 98, 22, 43,
14, 6, 22, 61, 26, 69, 21, 49, 72, 53,
84, 2, 52, 95, 48, 72, 47, 65, 6, 25,
46, 37, 61, 13, 32, 21, 32, 89, 30, 55,
31, 86, 46, 74, 32, 88, 19, 48, 36, 79,
76, 69, 76, 51, 85, 11, 40, 89, 26, 74,
85, 13, 61, 7, 64, 76, 47, 52, 90, 45
]);
```

Resource-Constrained Project Scheduling Problem (RCPSP) (Bourreau et al., 2019 [7])

- RCPSP with different approaches
- Different solvers, Choco-Solver, OPL Studio
- Complete Java projects
- Focus on modelling alternatives, performance
- Partial search (LDS)
- Also considers job-shop

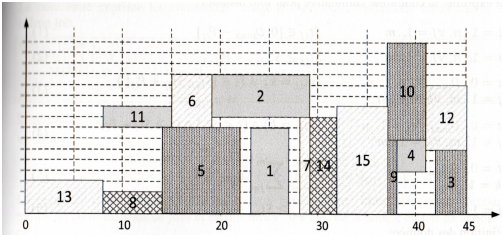


Figure 4-31. Solution optimale de valeur 45 obtenue avec la modélisation cumulative

Common Points

- A good number of scheduling problems are presented
- Often not in a form that allows Constraint Acquisition to work
- Needs a lot of work to present data and solutions in machine readable form
- Resulting models are easy for tools to find, even with single (few) positive examples

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Motivation

- More and more papers attach data
- But, every paper uses different format
- CA ideally should be able to deal with these
- Broad basis for requirements analysis
- Most papers do not make it easy to understand data

Methodology

- Use DBLP as primary source
- Extract relevant meta-data
- Text analysis of pdf to find shared concepts
- Manual extraction of some features

Existing Literature Surveys

- Optimal methods for resource allocation and scheduling: a cross-disciplinary survey. Lombardi, Milano. 2012 [31].
  - Compares CP, MIP and hybrid methods
  - Gives examples of models and solution methods
  - From 2012, a lot of progress since then
- Applications of constraint programming in production scheduling problems: A descriptive bibliometric analysis. Prata, Abreu, and Nagano. 2024 [36].
  - Deeply flawed paper: data, methodology and analysis
  - Only focuses on flow/job/open shop

Literature Survey - Recent Articles

Table 3: Articles from bibtex

Key	Authors	Title	LC	Cite	Year	Journal	Pages
PrataAN23 PrataAN23	Bruno A. Prata, Levi R. Abreu, Marcelo S. Nagano	Applications of constraint programming in production scheduling problems: A descriptive bibliometric analysis		[312]	2024	Results in Control and Optimization	1
abs-2402-00459 abs-2402-00459	S. Nguyen, Dhananjay R. Thiruvady, Y. Sun, M. Zhang	Genetic-based Constraint Programming for Resource Constrained Job Scheduling		[279]	2024	CoRR	null
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	NO	[90]	2023	Int. J. Prod. Res.	20
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		[7]	2023	IEEE Access	16
Caballero23 Caballero23	Jordi Coll Caballero	Scheduling through logic-based tools		[71]	2023	Constraints An Int. J.	1
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		[157]	2023	Central Eur. J. Oper. Res.	25
IsikYA23 IsikYA23	Eyüp Ensar Isik, Seyda Topaloglu Yildiz, Özge Satir Akpunar	Constraint programming models for the hybrid flow shop scheduling problem and its extensions		[186]	2023	Soft Comput.	28
LacknerMMWW23 LacknerMMWW23	M. Lackner, C. Mrkvicka, N. Musliu, D. Walkiewicz, F. Winter	Exact methods for the Oven Scheduling Problem		[224]	2023	Constraints An Int. J.	42
MontemanniD23 MontemanniD23	R. Montemanni, M. Dell'Amico	Solving the Parallel Drone Scheduling Traveling Salesman Problem via Constraint Programming		[268]	2023	Algorithms	1
MontemanniD23a MontemanniD23a	R. Montemanni, M. Dell'Amico	Constraint programming models for the parallel drone scheduling vehicle routing problem		[267]	2023	EURO J. Comput. Optim.	1
ShaikhK23 ShaikhK23	Aftab Ahmed Shaikh, Abdullah Ayub Khan	Management of electronic ledger: a constraint programming approach for solving curricula scheduling problems	NO	[336]	2023	Int. J. Electron. Secur. Digit. Forensics	12
YuraszeckMCCR23 YuraszeckMCCR23	F. Yuraszeck, E. Montero, D. Canut-de-Bon, N. Cuneo, M. Rojel	A Constraint Programming Formulation of the Multi-Mode Resource-Constrained Project Scheduling Problem for the Flexible Job Shop Scheduling Problem		[406]	2023	IEEE Access	11
abs-2305-19888 abs-2305-19888	V. Heinz, A. Novák, M. Vlk, Z. Hanzálek	Constraint Programming and Constructive Heuristics for Parallel Machine Scheduling with Sequence-Dependent Setups and Common Servers		[170]	2023	CoRR	null
abs-2306-05747 abs-2306-05747	P. Tassel, M. Gebser, K. Schekotihin	An End-to-End Reinforcement Learning Approach for Job-Shop Scheduling Problems Based on Constraint Programming		[356]	2023	CoRR	null
abs-2312-13682 abs-2312-13682	G. Perez, G. Glorian, W. Suijlen, A. Lallouet	A Constraint Programming Model for Scheduling the Unloading of Trains in Ports: Extended		[300]	2023	CoRR	null
AbreuN22 AbreuN22	Levi Ribeiro de Abreu, Marcelo Seido Nagano	A new hybridization of adaptive large neighborhood search with constraint programming for open shop scheduling with sequence-dependent setup times		[89]	2022	Comput. Ind. Eng.	1
BourreauGGLT22 BourreauGGLT22	E. Bourreau, T. Garaix, M. Gondran, P. Lacomme, N. Tchernev	A constraint-programming based decomposition method for the Generalised Workforce Scheduling and Routing Problem (GWSRP)	NO	[68]	2022	Int. J. Prod. Res.	19
CampeauG22 CampeauG22	L. Campeau, M. Gamache	Short- and medium-term optimization of underground mine planning using constraint programming		[72]	2022	Constraints An Int. J.	18
FetgoD22 FetgoD22	Sévérine Betmbe Fetgo, Clémentin Tayou Djamégni	Horizontally Elastic Edge-Finder Algorithm for Cumulative Resource Constraint Revisited		[116]	2022	Oper. Res. Forum	null
HeinzNVH22 HeinzNVH22	V. Heinz, A. Novák, M. Vlk, Z. Hanzálek	Constraint Programming and constructive heuristics for parallel machine scheduling with sequence-dependent setups and common servers		[169]	2022	Comput. Ind. Eng.	1

Literature Survey - Extracted Concepts

Table 7: Keywords by Work and Domains

Work	Concepts	Classification	Constraints	ProgLanguages	CPSystems	Areas	Industries	Benchmarks	Algorithm
PrataAN23 [312]	scheduling, order, job, task, activity, resource, machine, precedence, preempt, sequence dependent setup, inventory, make span, completion time, flow time, lateness, tardiness, earliness, flow shop, job shop, open shop, release date, due date, setup time, distributed, re scheduling, batch process	single machine, parallel machine, Open Shop Scheduling Problem	cumulative, circuit		CHIP	aircraft, robot, energy price, dairy	manufacturing industry	benchmark, real world, real life, http://, https://	time tabling
abs-2402-00459 [279]	scheduling, order, job, task, resource, machine, precedence, completion time, tardiness, earliness, job shop, due date, multi agent	single machine	cumulative, disjunctive, bin packing		or tools		mining industry	benchmark, generated instance, instance generator, real world, http://, https://, github	
AbreuNP23 [90]									
AkramNHRSA23 [7]	scheduling, order, task, resource, machine, preempt, completion time, distributed		bin packing	python	or tools	agriculture, medical		benchmark, https://	
Caballero23 [71]	scheduling, resource	RCPSP						http://, https://	
GurPAE23 [157]	scheduling, order, resource, machine, inventory, distributed, re scheduling		cumulative		cplex	physician, nurse, patient, COVID		real life, https://	
IsikYA23 [186]	scheduling, order, job, task, resource, machine, precedence, preempt, sequence dependent setup, transportation, make span, cmax, completion time, tardiness, earliness, flow shop, job shop, release date, due date, setup time, distributed, batch process	single machine, parallel machine	cumulative, circuit, nooverlap, endbeforestart		cplex, OPL	medical, robot	steel industry	benchmark, generated instance, real world, real life, http://, https://	energetic reasoning
LacknerMMWW23 [224]	scheduling, order, job, task, machine, make span, lateness, tardiness, earliness, job shop, release date, due date, setup time, batch process	single machine, parallel machine, OSP	alternative constraint, cumulative, disjunctive, nooverlap, endbeforestart, bin packing		cplex, gurobi, or tools, OPL, cpo, chuffed, minizinc	semiconductor, oven scheduling	electronics industry, manufacturing industry, steel industry	benchmark, instance generator, random instance, real life, industrial partner, http://, https://, zenodo	time tabling
MontemanniD23 [268]	scheduling, order, task, resource, machine, distributed		circuit	python	gurobi, or tools	robot		benchmark, supplementary material, https://	
MontemanniD23a [267]	scheduling, order, task, transportation, completion time		circuit	python	or tools			benchmark, http://, https://	

Literature Survey - Supplementary Materials

Table 4: Article Properties

Key	Title	CP System	Data Avail	Sol Avail	Code Avail	Based On	Classification	Constraints
PrataAN23 PrataAN23	Applications of constraint programming in production scheduling problems: A descriptive bibliometric analysis	-	-		-	-	survey	-
abs-2402-00459 abs-2402-00459	Genetic-based Constraint Programming for Resource Constrained Job Scheduling	OR-Tools	y		n	-	RCJS	cumulatives
AbreuNP23 AbreuNP23	A new two-stage constraint programming approach for open shop scheduling problem with machine blocking	?	?		?	?	?	?
AkramNHRSA23 AkramNHRSA23	Joint Scheduling and Routing Optimization for Deterministic Hybrid Traffic in Time-Sensitive Networks Using Constraint Programming	OR-Tools	n		n	-	TSN	-
Caballero23 Caballero23	Scheduling through logic-based tools	SAT	-		-	PhD Thesis	RCPSP	-
GurPAE23 GurPAE23	Operating room scheduling with surgical team: a new approach with constraint programming and goal programming	Cplex	n		n	-	-	-
IsikYA23 IsikYA23	Constraint programming models for the hybrid flow shop scheduling problem and its extensions	OPL CP Opt	y		y	-	HFSP	alternative endBeforeStart noOverlap cumulative
LacknerMMWW23 LacknerMMWW23	Exact methods for the Oven Scheduling Problem	MiniZinc OPL	DZN JSON		y	[223]	OSP	alternative noOverlap forbidExtent
MontemanniD23 MontemanniD23	Solving the Parallel Drone Scheduling Traveling Salesman Problem via Constraint Programming	OR-Tools	ref	y	n	-	PDSTSP	circuit
MontemanniD23a MontemanniD23a	Constraint programming models for the parallel drone scheduling vehicle routing problem	OR-Tools	ref		n	-	PDSTSP	circuit multipleCircuit
ShaikhK23 ShaikhK23	Management of electronic ledger: a constraint programming approach for solving curricula scheduling problems	?	?		?	?	?	?
YuraszeckMCCR23 YuraszeckMCCR23	A Constraint Programming Formulation of the Multi-Mode Resource-Constrained Project Scheduling Problem for the Flexible Job Shop Scheduling Problem	CP Opt	ref		n	-	FJSSP	alternative endBeforeStart cumulative
abs-2305-19888 abs-2305-19888	Constraint Programming and Constructive Heuristics for Parallel Machine Scheduling with Sequence-Dependent Setups and Common Servers	CP Opt Gurobi	y	y	n	-	$P\|seq, ser\|C_{max}$	alternative noOverlap cumulative
abs-2306-05747 abs-2306-05747	An End-to-End Reinforcement Learning Approach for Job-Shop Scheduling Problems Based on Constraint Programming	custom Choco	ref		n	-	JSSP	noOverlap
abs-2312-13682 abs-2312-13682	A Constraint Programming Model for Scheduling the Unloading of Trains in Ports: Extended	custom	n		n	-	SUTP	table disjunctive
AbreuN22 AbreuN22	A new hybridization of adaptive large neighborhood search with constraint programming for open shop scheduling with sequence-dependent setup times	Cplex CP Opt	y		n	-	OSSPST	noOverlap
BourreauGGLT22 BourreauGGLT22	A constraint-programming based decomposition method for the Generalised Workforce Scheduling and Routing Problem (GWSRP)							
CampeauG22 CampeauG22	Short- and medium-term optimization of underground mine planning using constraint programming	CP Opt	ref		n			pulse alwaysIn endBeforeStart noOverlap
FetgoD22 FetgoD22	Horizontally Elastic Edge-Finder Algorithm for Cumulative Resource Constraint Revisited							
HeinzNVH22	Constraint Programming and constructive heuristics for							

Literature Survey - The same for Papers

Table 2: Paper Properties

Key	Title	CP System	Data Avail	Sol Avail	Code Avail	Based On	Classification	Constraints
AalianPG23 AalianPG23	Optimization of Short-Term Underground Mine Planning Using Constraint Programming	CP Opt	n		n			?
Bit-Monmot23 Bit-Monmot23	Enhancing Hybrid CP-SAT Search for Disjunctive Scheduling	ARIES CP Opt OR-Tools Mistral	y		y	-	JSSP OSSP	-
EfthymiouY23 EfthymiouY23	Predicting the Optimal Period for Cyclic Hoist Scheduling Problems	OR-Tools	n		n	-	CHSP	-
JuvinHHL23 JuvinHHL23	An Efficient Constraint Programming Approach to Preemptive Job Shop Scheduling	CP Opt Mistral	ref		y		PJSSP	endBeforeStart span noOverlap
JuvinHL23 JuvinHL23	Constraint Programming for the Robust Two-Machine Flow-Shop Scheduling Problem with Budgeted Uncertainty	CP Opt Cplex	ref		n	-	Perm FSSP	endBeforeStart noOverlap sameSequence
KameugneFND23 KameugneFND23	Horizontally Elastic Edge Finder Rule for Cumulative Constraint Based on Slack and Density	?	BL PSPlib		n	-	RCPSPs	cumulative
KimCMLLP23 KimCM-LLP23	Iterated Greedy Constraint Programming for Scheduling Steelmaking Continuous Casting	Gurobi OR-Tools	y		n	-	SCC	alternative noOverlap
Mehdizadeh-Somarin23 Mehdizadeh-Somarin23	A Constraint Programming Model for a Reconfigurable Job Shop Scheduling Problem with Machine Availability	CP Opt	n		n	-	JSSP RMS	alternative endBeforeStart noOverlap
PerezGSL23 PerezGSL23	A Constraint Programming Model for Scheduling the Unloading of Trains in Ports	custom	n		n	-	SUTP	table disjunctive
PovedaAA23 PovedaAA23	Partially Preemptive Multi Skill/Mode Resource-Constrained Project Scheduling with Generalized Precedence Relations and Calendars	CP Opt MiniZinc Chuffed	y		y		PP-MS-MMRCPSP/max-cal	
SquillaciPR23 Squil-laciPR23	Scheduling Complex Observation Requests for a Constellation of Satellites: Large Neighborhood Search Approaches	Cplex Studio	y		n	-	EOSP	?
TardivoDFMP23 Tardi-voDFMP23	Constraint Propagation on GPU: A Case Study for the Cumulative Constraint	MiniCPP MiniZinc	PSPLib BL Pack		y	-	RCPSP	cumulative
TasselGS23 TasselGS23	An End-to-End Reinforcement Learning Approach for Job-Shop Scheduling Problems Based on Constraint Programming	custom Choco	ref		y	-	JSSP	noOverlap
WangB23 WangB23	Dynamic All-Different and Maximal Cliques Constraints for Fixed Job Scheduling	FaCiLe	(y)		n	[390]	FJS	-
YuraszeckMC23 YuraszeckMC23	A competitive constraint programming approach for the group shop scheduling problem	CP Opt	ref		n	-	GSSP	noOverlap endBeforeStart
ArmstrongGOS22 Arm-strongGOS22	A Two-Phase Hybrid Approach for the Hybrid Flexible Flowshop with Transportation Times	CP Opt	(y)		-	[13]	$HFFm\|tt\|C_{\max}$	endBeforeStart alternative cumulative noOverlap
BoudreaultSLQ22 BoudreaultSLQ22	A Constraint Programming Approach to Ship Refit Project Scheduling	MiniZinc Chuffed			y	-	RCPSP	cumulative
GeitzGSSW22 GeitzGSSW22	Solving the Extended Job Shop Scheduling Problem with AGVs - Classical and Quantum Approaches	firstCS QUBO	y		n	-	JSSP	
LiFJZLL22 LiFJZLL22	Constraint Programming for a Novel Integrated Optimization of Blocking Job Shop Scheduling and Variable-Speed Transfer Robot Assignment	OPL CP Opt	ref		n	-	BJSSP	endBEforeStart alternative noOverlap
OuelletQ22 OuelletQ22	A MinCumulative Resource Constraint	Choco	y		y	-		cumulative minCumulative
OujanaAYB22 Ou-janaAYB22	Solving a realistic hybrid and flexible flow shop scheduling problem through constraint programming: industrial case	CP Opt	n		n	-	HFFS	alternative span

Literature Survey - Application Areas

Table 8: Papers by Domain and Keyword

Domain	Keyword	High	Medium	Low
ApplicationAreas	crew scheduling	PourDERB18[308]	Mason01[259], Touraivane95[366]	WangB23[391], HeimzNVH22[169], HachemiGR11[158], BeldiceanuC02[42]
ApplicationAreas	dairies			Bartak02[33], Bartak02a[32]
ApplicationAreas	dairy	EscobetPQPRA19[110]	PrataAN23[312]	
ApplicationAreas	datacenter	HermenierDL11[174]		GalleguillosKSB19[124], Madi-WambaLOBM17[252], IfrimOS12[185], LetortBC12[228]
ApplicationAreas	datacentre			
ApplicationAreas	day ahead market			
ApplicationAreas	deep space			
ApplicationAreas	earth observation	SquillaciPR23[346], VerfaillieL01[375]	BensanaLV99[51]	PraletLJ15[311], SimoninAHL15[342], KelarevaTK13[197], OddiPCC03[288]
ApplicationAreas	earth orbit			SquillaciPR23[346]
ApplicationAreas	electroplating		RodosekW98[320]	EfthymiouY23[106], WallaceY20[389], NovasH12[286]
ApplicationAreas	energy price	GrimesIOS14[152], IfrimOS12[185]		PrataAN23[312], EscobetPQPRA19[110], BenediktSMVH18[49], He0GLW18[161], LimHTB16[234]
ApplicationAreas	farming			WinterMMW22[396], Astrand0F21[20]
ApplicationAreas	forestry	HachemiGR11[158]		Astrand0F21[20]
ApplicationAreas	hoist	EfthymiouY23[106], WallaceY20[389], RodosekW98[320]	NovasH12[286], BonfiettiLBM11[61]	AstrandJZ18[21], BonfiettiLBM12[62], LombardiBMB11[242], KorbasY09[206], PapaB98[296]
ApplicationAreas	medical	ShinBBHO18[338], WangMD15[392], TopalogluO11[364]	HechingH16[163], DejemeppeD14[93], RendlPHPR12[318]	AkramNHRSA23[7], IsikYA23[186], AbreuN22[89], GeibingerKKMMW21[133], FrimodigS19[121], Novas19[284], abs-1902-01193[8], GedikKEK18[132], BoothNB16[65], DoulabiRP14[103], Simonis07[344]
ApplicationAreas	nurse	GurPAE23[157], abs-1902-01193[8], ShinBBHO18[338], WangMD15[392], RendlPHPR12[318], Simonis07[344], Mason01[259]	OuelletQ22[291], GeibingerKKMMW21[133], GeibingerMM21[136], FrohnerTR19[122]	PerezGSL23[299], abs-2312-13682[300], FrimodigS19[121], NishikawaSTT18a[281], GedikKEK18[132], DoulabiRP14[103], TopalogluO11[364]
ApplicationAreas	offshore		SubulanC22[347]	BoudreaultSLQ22[67]
ApplicationAreas	oven scheduling	LacknerMMWW23[224], LacknerMMWW21[223]		
ApplicationAreas	patient	GurPAE23[157], FrimodigS19[121], ShinBBHO18[338], HechingH16[163], WangMD15[392], DejemeppeD14[93], RendlPHPR12[318], TopalogluO11[364]	GeibingerKKMMW21[133]	MurinR19[273], DoulabiRP14[103], Simonis07[344]
ApplicationAreas	perfect square	BeldiceanuCDP11[43], BeldiceanuCP08[44]		
ApplicationAreas	physician	GeibingerKKMMW21[133], ShinBBHO18[338]		GurPAE23[157], FrimodigS19[121], WangMD15[392], TopalogluO11[364]
ApplicationAreas	pipeline	LopesCSM10[246], MouraSCL08[271], MouraSCL08a[270], ErtlK91[109]	BeniniBGM06[50], WolinskiKG04[399]	EfthymiouY23[106], PopovicCGNC22[307], HanenKP21[159], NishikawaSTT18[280], NishikawaSTT18a[281], LaborieRSV18[222], GilesH16[140], GoelSHFS15[144], SimoninAHL15[342], NovasH10[285], BarlattCG08[31], Wolf03[397], KuchcinskiW03[218], GruianK98[155], Darby-DowmanLMZ97[86], SimonisC95[345]
ApplicationAreas	radiation therapy	FrimodigS19[121]		
ApplicationAreas	railway	PourDERB18[308], CappartS17[73], Acuna-AgostMFG09[4], AronssonBK09[15], Geske05[139], MartinPY01[258]	LaborieRSV18[222], Mason01[259]	BogaerdtW19[371], ZhouGL15[416], AbrilSB05[3], Wallace96[388]
ApplicationAreas	real time pricing			LimHTB16[234]
ApplicationAreas	rectangle packing	YangSS19[402]		MossigeGSMC17[269], VilimLS15[385], BeldiceanuCDP11[43], SchuttW10[334], BeldiceanuCP08[44]

Literature Survey - Frequent Authors

Table 5: Co-Authors of Articles/Papers

Author	Entries
Andreas Schutt	YangSS19[402] KreterSS17[217] YoungFS17[403] GoldwaserS17[146] SchuttS16[333] SzerediS16[351] KreterSS15[216] EvenSH15[111] EvenSH15a[112] SchuttFS13[330] cpaior-SchuttFS13[329] GuSS13[156] SchuttCSW12[328] SchuttFSW11[332] SchuttW10[334] SchuttFSW09[331]
Nicolas Beldiceanu	Madi-WambaLOBM17[252] Madi-WambaB16[251] LetortCB15[230] LetortCB13[229] LetortBC12[228] ClercqPBJ11[81] BeldiceanuCDP11[43] BeldiceanuCP08[44] PoderB08[303] BeldiceanuP07[45] PoderBS04[304] BeldiceanuC02[42] AggounB92[5]
J. Christopher Beck	TangB20[352] BoothNB16[65] KoschB14[208] HeinzSB13[168] HeinzKB13[165] HeinzB12[164] KovacsB11[210] BeckFW11[38] WatsonB08[393] KovacsB08[209] CarchraeBF05[74] WuBB05[401] BeckDF97[37]
Emmanuel Hebrard	JuvinHHL23[188] AntuoriHHEN21[11] GodetLHS20[143] SimoninAHL15[342] SialaAH15[340] BessiereHMQW14[53] SimoninAHL12[341] BillautHL12[54] GrimesH11[150] GrimesH10[149] GrimesHM09[151] HebrardTW05[162]
Peter J. Stuckey	YangSS19[402] DemirovicS18[95] KreterSS17[217] SchuttS16[333] KreterSS15[216] BurtLPS15[70] SchuttFS13[330] cpaior-SchuttFS13[329] GuSS13[156] SchuttCSW12[328] SchuttFSW11[332] SchuttFSW09[331]
Michele Lombardi	BonfiettiZLM16[64] LombardiBM15[241] BartoliniBBLM14[35] BonfiettiLM14[63] LombardiM12[245] BonfiettiLBM12[62] BonfiettiLBM11[61] LombardiBMB11[242] LombardiM10[244] LombardiM09[243] HoeveGSL07[373]
Pierre Lopez	JuvinHHL23[188] JuvinHL23[189] Polo-MejiaALB20[306] NattafAL17[277] SimoninAHL15[342] NattafAL15[276] SimoninAHL12[341] BillautHL12[54] LahimerLH11[225] TrojetHL11[367] LopezAKYG00[247]
Michela Milano	BonfiettiZLM16[64] LombardiBM15[241] BartoliniBBLM14[35] BonfiettiLM14[63] LombardiM12[245] BonfiettiLBM12[62] BonfiettiLBM11[61] LombardiBMB11[242] LombardiM10[244] LombardiM09[243] BeniniBGM06[50]
Petr Vilím	LaborieRSV18[222] VilimLS15[385] Vilim11[382] Vilim09[380] cpaior-Vilim09[381] VilimBC05[384] Vilim05[379] VilimBC04[383] Vilim04[378] Vilim03[377] Vilim02[376]
Christian Artigues	PovedaAA23[309] PohlAK22[305] Polo-MejiaALB20[306] NattafAL17[277] SimoninAHL15[342] NattafAL15[276] SialaAH15[340] SimoninAHL12[341] ArtiguesBF04[16] ArtiguesR00[17]
John N. Hooker	Hooker17[181] HechingH16[163] CireCH13[80] CobanH10[82] Hooker06[180] Hooker05[178] cp-Hooker05[179] Hooker04[177] HookerY02[182]
Claude-Guy Quimper	BoudreaultSLQ22[67] OuelletQ22[291] Mercier-AubinGQ20[263] FahimiOQ18[113] KameugneFGOQ18[192] OuelletQ18[290] GingrasQ16[141] BessiereHMQW14[53] OuelletQ13[289]
Pierre Schaus	CappartS17[73] CauwelaertDMS16[76] DejemeppeCS15[92] GayHLS15[128] GayHS15[129] cpaior-GayHS15[130] HoundjiSWD14[183] GaySS14[131] SchausHMCMD11[326]
Pascal Van Hentenryck	FontaineMH16[117] EvenSH15[111] EvenSH15a[112] SchausHMCMD11[326] MonetteDH09[266] DoomsH08[102] HentenryckM08[173] HentenryckM04[172] DincbasSH90[101]
Philippe Baptiste	BaptisteB18[26] Baptiste09[25] BaptisteLPN06[27] ArtiouchineB05[18] BaptisteP00[29] PapaB98[296] BaptisteP97[28] PapeB97[295]
Mats Carlsson	WessenCS20[394] MossigeGSMC17[269] LetortCB15[230] LetortCB13[229] LetortBC12[228] BeldiceanuCDP11[43] BeldiceanuCP08[44] BeldiceanuC02[42]
Nysret Musliu	LacknerMMWW23[224] WinterMMW22[396] LacknerMMWW21[223] GeibingerKKMMW21[133] GeibingerMM21[136] GeibingerMM19[135] abs-1911-04766[134] KletzanderM17[204]
Helmut Simonis	ArmstrongGOS22[14] ArmstrongGOS21[13] GrimesIOS14[152] IfrimOS12[185] Simonis07[344] SimonisC95[345] Simonis95[343] DincbasSH90[101]
Alessio Bonfietti	BonfiettiZLM16[64] Bonfietti16[60] LombardiBM15[241] BonfiettiLM14[63] BonfiettiLBM12[62] BonfiettiLBM11[61] LombardiBMB11[242]
Zdenek Hanzálek	Mehdizadeh-Somarin23[260] abs-2305-19888[170] HeinzNVH22[169] VlkHT21[387] BenediktMH20[48] BenediktSMVH18[49] KelbelH11[198]
Philippe Laborie	LunardiBLRV20[249] LaborieRSV18[222] Laborie18a[221] MelgarejoLS15[6] VilimLS15[385] Laborie09[220] BaptisteLPN06[27]
Gabriela P. Henning	NovaraNH16[283] NovasH14[287] NovasH12[286] NovasH10[285] ZeballosQH10[409] ZeballosH05[408] QuirogaZH05[317]
Stefan Heinz	HeinzSB13[168] HeinzKB13[165] HeinzSSW12[166] HeinzB12[164] HeinzS11[167] BertholdHLMS10[52]
András Kovács	KovacsB11[210] KovacsK11[212] KovacsB08[209] KovacsV06[214] KovacsEKV05[211] KovacsV04[213]
Emmanuel Poder	BeldiceanuCDP11[43] abs-0907-0939[302] BeldiceanuCP08[44] PoderB08[303] BeldiceanuP07[45] PoderBS04[304]
Mark Wallace	WallaceY20[389] He0GLW18[161] SchuttFSW09[331] SakkoutW00[325] RodosekW98[320] Wallace96[388]
Roman Barták	BartakS11[34] VilimBC05[384] VilimBC04[383] Bartak02[33] Bartak02a[32]
Yves Deville	HoundjiSWD14[183] DejemeppeD14[93] SchausHMCMD11[326] MonetteDH09[266] MonetteDD07[265]
Thibaut Feydy	YoungFS17[403] SchuttFS13[330] cpaior-SchuttFS13[329] SchuttFSW11[332] SchuttFSW09[331]
Roger Kameugne	KameugneFND23[193] KameugneFGOQ18[192] Kameugne15[191] KameugneFSN14[195] KameugneFSN11[194]
Claude Le Pape	BaptisteLPN06[27] BaptisteP00[29] PapaB98[296] BaptisteP97[28] PapeB97[295]
Juan M. Novas	Novas19[284] NovaraNH16[283] NovasH14[287] NovasH12[286] NovasH10[285]
Louis-Martin Rousseau	DoulabiRP16[104] PesantRR15[301] DoulabiRP14[103] ChapadosJR11[78] HachemiGR11[158]
André A. Ciré	CireCH13[80] LopesCSM10[246] MouraSCL08[271] MouraSCL08a[270]
Luca Benini	BonfiettiLBM12[62] BonfiettiLBM11[61] LombardiBMB11[242] BeniniBGM06[50]
Cyrille Dejemeppe	CauwelaertDMS16[76] Dejemeppe16[91] DejemeppeCS15[92] DejemeppeD14[93]
Steven Gay	GayHLS15[128] GayHS15[129] cpaior-GayHS15[130] GaySS14[131]
Tobias Geibinger	GeibingerKKMMW21[133] GeibingerMM21[136] GeibingerMM19[135] abs-1911-04766[134]
Diarmuid Grimes	GrimesIOS14[152] GrimesH11[150] GrimesH10[149] GrimesHM09[151]
Krzysztof Kuchcinski	WolinskiKG04[399] WolinskiKG04a[400] KuchcinskiW03[218] GruianK98[155]
Laurent Michel	TardivoDFMP23[354] SchausHMCMD11[326] HentenryckM08[173] HentenryckM04[172]
Florian Mischek	GeibingerKKMMW21[133] GeibingerMM21[136] GeibingerMM19[135] abs-1911-04766[134]

Most Recent Papers/Articles with Supplementary Materials

Key	Size	Instances	MetaData	Format	Solutions	Checker
AbreuN22 [10]	1.3MB	192	n	TS	n	n
AntuoriHHEN21 [1]	23.3MB	120	n	TS	n	n
ArmstrongGOS21 [4]	11MB	225	n	dzn	n	n
BenderWS21 [5]	116KB	84	y	TS	n	n
Bit-Monnot23 [6]	23.5MB	357	n	TS	n	n
GeibingerKKMMW21 [15]	40KB	3	-	dzn	n	n
GeibingerMM21 [16]	13.9MB	33	n	xml	y	n
GeitzGSSW22 [17]	16.0KB	8	y	json	n	n
IsikYA23 [26]	3.9MB	90	n	xlsx	y	n
KimCMLLP23 [28]	4.1MB	4	y	csv	n	n
KovacsTKSG21 [29]	138MB	18	n	json json	n	n

AbreuN22 [10]

- Two stage open shop
- No buffer space
- Tasks of a job must follow each other without delay
- C_{max} objective

```
1
2   M0
3   33 436 108
4   401 221 132
5   177 259 155
6
7   M1
8   120 26 280
9   184 250 252
10  214 25 469
11
12  M2
13  393 53 262
14  70 24 420
15  463 304 168
16
17
```

AntuoriHHEN21 [1]

- Car manufacturing workshop
- Repetitive single vehicle pickup and delivery problem with time windows and capacity constraint
- Trolleys move components between two stages

```
492
8000

0 0 0 PF 1950 0 40 0 3625 2
1 0 0 DF 1950 1 40 0 3625 2
2 0 0 PE 1950 1 15 0 3625 2
3 0 0 DE 1950 0 15 0 3625 2
4 0 1 PF 1950 0 40 3625 7250 2
5 0 1 DF 1950 1 40 3625 7250 2
6 0 1 PE 1950 1 15 3625 7250 2
7 0 1 DE 1950 0 15 3625 7250 2
8 0 2 PF 1950 0 40 7250 10875 2
9 0 2 DF 1950 1 40 7250 10875 2
10 0 2 PE 1950 1 15 7250 10875 2
11 0 2 DE 1950 0 15 7250 10875 2
12 0 3 PF 1950 0 40 10875 14500 2
13 0 3 DF 1950 1 40 10875 14500 2
14 0 3 PE 1950 1 15 10875 14500 2
15 0 3 DE 1950 0 15 10875 14500 2
16 0 4 PF 1950 0 40 14500 18125 2
17 0 4 DF 1950 1 40 14500 18125 2
18 0 4 PE 1950 1 15 14500 18125 2
19 0 4 DE 1950 0 15 14500 18125 2
20 0 5 PF 1950 0 40 18125 21750 2
21 0 5 DF 1950 1 40 18125 21750 2
22 0 5 PE 1950 1 15 18125 21750 2
23 0 5 DE 1950 0 15 18125 21750 2
24 0 6 PF 1950 0 40 21750 25375 2
25 0 6 DF 1950 1 40 21750 25375 2
```

ArmstrongGOS21 [4]

- Hybrid, flexible flowshop with transportation times between machines
- Instances in MiniZinc .dzn format
- Single file per instance
- Matches program in paper
- Integers, String, Arrays, Sets
- Tedious to parse for other solvers
- Could now be replaced by JSON
- Checker is easy to add

```
% JSJ flowshop data
T = 1..154;
P = 1..134;
M = 1..80;
S = 1..8;
tuples = 1..800;
lb = 62;
ub = 63;
m = 80;
duration=
[3,10,4,4,6,8,7,4,1,4,7,10,1,4,9,9,9,3,1,1,6,8,6,8,2,3,6,6,8
,5,9,4,3,3,7,10,5,10,8,3,10,9,2,6,6,4,7,7,9,4,10,8,8,5,9,4,3
capacity = [10,10,10,10,10,10,10,10];
stage =
[1,2,3,4,5,6,7,8,1,2,3,4,5,6,7,8,1,2,3,5,6,7,1,2,3,4,5,6,7,8
5,6,7,8,1,2,3,4,5,6,7,8,1,2,3,4,5,6,7,8,1,2,3,4,5,6,7,8,1,2,
machines =
[{1,2,3,4,5,6,7,8,9,10},{11,12,13,14,15,16,17,18,19,20},{21,
,78,79,80},{1,2,3,4,5,6,7,8,9,10},{11,12,13,14,15,16,17,18,1
4,75,76,77,78,79,80},{1,2,3,4,5,6,7,8,9,10},{11,12,13,14,15,
14,15,16,17,18,19,20},{21,22,23,24,25,26,27,28,29,30},{31,32
{11,12,13,14,15,16,17,18,19,20},{21,22,23,24,25,26,27,28,29,
7,8,9,10},{11,12,13,14,15,16,17,18,19,20},{21,22,23,24,25,26
2,3,4,5,6,7,8,9,10},{11,12,13,14,15,16,17,18,19,20},{21,22,2
79,80},{1,2,3,4,5,6,7,8,9,10},{11,12,13,14,15,16,17,18,19,20
0,9,10},{11,12,13,14,15,16,17,18,19,20},{21,22,23,24,25,26,2
5,26,27,28,29,30},{31,32,33,34,35,36,37,38,39,40},{41,42,43,
22,23,24,25,26,27,28,29,30},{31,32,33,34,35,36,37,38,39,40},
9,20},{21,22,23,24,25,26,27,28,29,30},{41,42,43,44,45,46,47,
26,27,28,29,30},{31,32,33,34,35,36,37,38,39,40},{41,42,43,44
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20},{21,22,23,24,25,26,27,28,29,30},{31,32,33,34,35,36,37,38
,17,18,19,20},{21,22,23,24,25,26,27,28,29,30},{31,32,33,34,3
3,14,15,16,17,18,19,20},{21,22,23,24,25,26,27,28,29,30},{31,
},{11,12,13,14,15,16,17,18,19,20},{21,22,23,24,25,26,27,28,2
6,7,8,9,10},{11,12,13,14,15,16,17,18,19,20},{21,22,23,24,25,
1,2,3,4,5,6,7,8,9,10},{11,12,13,14,15,16,17,18,19,20},{21,22
8,79,80}];
proc =
[{1,2|2,3|3,4|4,5|5,6|6,7|7,8|9,10|10,11|11,12|12,13|13,14|1
9|49,50|50,51|51,52|52,53|53,54|55,56|56,57|57,58|58,59|59,6
4,95|95,96|96,97|97,98|99,100|100,101|101,102|102,103|103,10
|129,130|131,132|132,133|133,134|134,135|135,136|136,137|137
transportTime =
[{1,11,1|1,12,2|1,13,3|1,14,4|1,15,5|1,16,6|1,17,7|1,18,8|1,
4,1|4,15,2|4,16,3|4,17,4|4,18,5|4,19,6|4,20,7|5,11,5|5,12,4|
18,2|7,19,3|7,20,4|8,11,8|8,12,7|8,13,6|8,14,5|8,15,4|8,16,3
,1|11,21,1|11,22,2|11,23,3|11,24,4|11,25,5|11,26,6|11,27,7|1
3,30,8|14,21,4|14,22,3|14,23,2|14,24,1|14,25,2|14,26,3|14,27
```

BenderWS21 [5]

- Corn harvest scheduling
- Harvesters and transport vehicles
- Pre-emptive MRCPSP with fast-tracking, sequence-dependent setup times and synchronization of two resource types
- Meta-data: Describes format of data

```
4,2,4
64,43
30,30
0,186.454,228.75,116.595,175.71
3,2,2,3,2,2,2,3
27.5399,14.5452,44.6473,6.2793,2.5734
35.4074,25.5414,44.8147,10.3621,22.0405

```

Bit-Monnot23 [6]

- Disjunctive Scheduling
- Solver focused
- Open-/job-shop examples
- Mix of strings and numbers
- Text stream
- Different formats for job shop and open shop instances

```
nb_jobs nb_machines
10 10 0 0 0 0
Times
88 68 94 99 67 89 77 99 86 92
72 50 69 75 94 66 92 82 94 63
83 61 83 65 64 85 78 85 55 77
94 68 61 99 54 75 66 76 63 67
69 88 82 95 99 67 95 68 67 86
99 81 64 66 80 80 69 62 79 88
50 86 97 96 95 97 66 99 52 71
98 73 82 51 71 94 85 62 95 79
94 71 81 85 66 90 76 58 93 97
50 59 82 67 56 96 58 81 59 96
Machines
5 9 7 6 2 3 10 8 1 4
6 4 7 5 3 9 1 2 8 10
10 9 1 2 7 6 8 5 3 4
8 3 2 5 4 7 6 1 10 9
4 5 10 9 1 3 7 6 8 2
2 5 6 7 9 3 8 10 4 1
8 2 5 4 1 9 3 6 7 10
5 7 4 3 2 6 8 1 9 10
1 7 4 8 2 3 5 6 9 10
4 1 2 9 8 10 7 5 6 3
```

GeibingerMM21 [16]

- Test lab Scheduling
- Real-world problem
- Extension of RCPSP
- Multiple files per instances
- XML format throughout

```xml
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    <Project code="1">
        <Name>Project 1</Name>
        <Priority>1</Priority>
        <CabinSafety>0.0</CabinSafety>
        <Tasks>
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                <Name>Task 1.1</Name>
                <Duration>9.747909850747426</Duration>
                <ReleaseDate>0</ReleaseDate>
                <DueDate>58</DueDate>
                <Deadline>65</Deadline>
                <WorkbenchRequired>false</WorkbenchRequired>
                <TaskModes>1 2</TaskModes>
                <AvailableWorkbenches></AvailableWorkbenches>
                <QualifiedEmployees>1 3 7</QualifiedEmployees>
                <PreferredEmployees>1 3 7</PreferredEmployees>
                <EquipmentRequirements>
                    <Group groupId="1">
                        <Demand>1</Demand>
                        <AvailableDevices>1 2</AvailableDevices>
                    </Group>
                </EquipmentRequirements>
            </Task>
        </Tasks>
        <LinkedTasks>
            <LinkedSet>1</LinkedSet>
        </LinkedTasks>
        <TaskFamilies>
            <Family name="FA" setup="1.7807819167841257">
                <Tasks>1</Tasks>
            </Family>
            <Family name="FB" setup="2.978012341838491 4"/>
        </TaskFamilies>
    </Project>
    <Project code="2">
        <Name>Project 2</Name>
        <Priority>1</Priority>
        <CabinSafety>0.0</CabinSafety>
        <Tasks/>
```
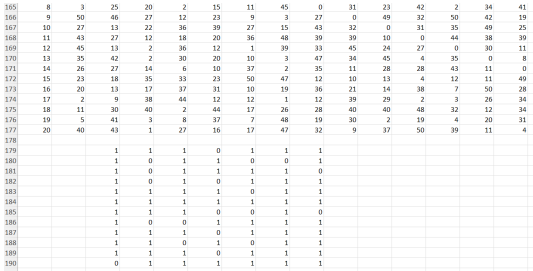

IsikYA23 [26]

- Extension of Hybrid Flow-shop (no-wait, blocking, sequence dependent setup)
- Uses Excel ./xlsx format for input and output
- Understandable as format of result summaries
- Horrible choice as data input format
  - Automatic type conversions by Excel
  - Hard to retrieve input data in original form



165	8	3	25	20	2	15	11	45	0	31	23	42	2	34	41	
166	9	50	46	27	12	23	9	3	27	0	49	32	50	42	19	
167	10	27	13	22	36	39	27	15	43	32	0	31	35	49	25	
168	11	43	27	12	18	20	36	48	39	39	10	0	44	38	39	
169	12	45	13	2	36	12	1	39	33	45	24	27	0	30	11	
170	13	35	42	2	30	20	10	3	47	34	45	4	35	0	8	
171	14	26	27	14	6	10	37	2	35	11	28	28	43	11	0	
172	15	23	18	35	33	23	50	47	12	10	13	4	12	11	49	
173	16	20	13	17	37	31	10	19	36	21	14	38	7	50	28	
174	17	2	9	38	44	12	12	1	12	39	29	2	3	26	34	
175	18	11	30	40	2	44	17	26	28	40	40	48	32	12	34	
176	19	5	41	3	8	37	7	48	19	30	2	19	4	20	31	
177	20	40	43	1	27	16	17	47	32	9	37	50	39	11	4	
178																
179			1	1	1	0	1	1	1							
180			1	0	1	1	0	0	1							
181			1	0	1	1	1	1	0							
182			1	0	1	0	1	1	1							
183			1	1	1	1	0	1	1							
184			1	1	1	1	1	1	1							
185			1	1	1	0	0	1	0							
186			1	0	0	1	1	1	1							
187			1	1	1	0	1	1	1							
188			1	1	0	1	0	1	1							
189			1	1	1	0	1	1	1							
190			0	1	1	1	1	1	1							

KovacsTKSG21 [29]

- Real-world work-load balancing problem
- Made-to-order printing machines
- Nice JSON format of data
- Real-life data
- One instance per file, one file per instance
- Task length given as float
- Machine capacity given as float

Challenges

- Data formats are often ad-hoc, token streams common
- Meaning of value depends on position in stream
- Solutions very rarely provided
  - If given, only one (best) solution is given
  - Sometimes can be generated from code which is provided
- Checkers non-existent
- For many papers, extracting the constraint model is not the challenge
  - Finding a good solution quickly enough is

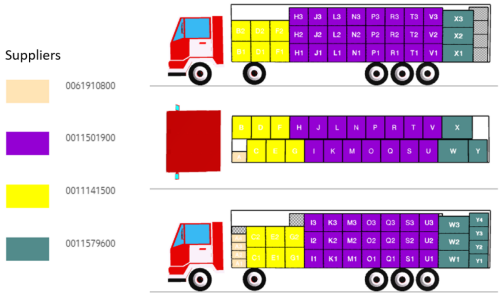
Table of Contents

Realistic Examples

- Two examples of a more complex nature
- Realistic, but not real problem set
- Show complexity of real-world problems

Roadef2022 Challenge

- Competition by French OR society Roadef, European OR society Euro
- Problem provided by Renault
- Schedule transport of components from suppliers to factories
- Decide when to transport item, how to pack them into trucks
- Decide how many resources (trucks) are needed
- Not a vehicle routing problem (routes predefined and given)
- Objective Minimize cost (resources plus earliness cost of items)



Input Data

Potential Trucks

```
Supplier code;Supplier loading order;Supplier dock;Supplier dock loading order;Plant code;Plant dock;Plant dock loading order;Product code;Arrival time;Id truck;Length;Width;Height;Max weight;Stack with multiple docks;Max density;Max weight on the bottom item in stacks;Cost;EMmm;EMmr;CM;CJfm;CJfc;CJfh;EM;EJhr;EJcr;EJeh
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```

Input Data (II)

Items to be Transported

```
Item ident;Supplier code;Supplier dock;Plant code;Plant dock;Product code;Package code;Number of items;Length;Width;Height;Weight;Nesting height;Stackability code;Forced orientation;Earliest arrival time;Latest arrival time;Inventory cost;Max stackability
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```

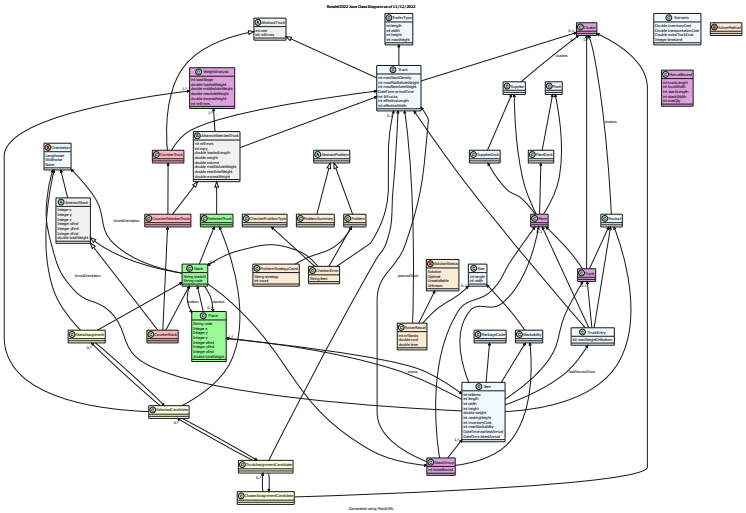
Parameters of Problem

```
Coefficient inventory cost;Coefficient transportation cost;Coefficient cost extra truck;timelimit (sec)
10;1;0,2;1800
```

Observations

- Data size varies between instances, but is typically (very) large
- Four stages of data availability, 150 instances in total
- One sample solution given
- But: Checker (in java) provided, normative
- Problem description 11+8 pages
- Data tables not normalized, contains much redundant information
- Normalizing data leads to UML Object Model on next slide

Resulting Object Model



Defined Output Format

- Three files
  - Trucks used
  - Stacks built
  - Pieces placed
- No direct link between planned and scheduled trucks
- Concept of stack is redundant
- One item results in multiple pieces
- Link between trucks, stacks, pieces and input data by string ids

Id truck	char	P380411201	
Loaded length	int	12500 mm	$max_{s \in \overline{Ss}_t} sx_s^e$
Weight of loaded items	float	1894,31	kg
Volume of loaded items	float	14,544	m^3
Weight on the middle axle of the trailer (em^m)	float	1875,83	kg
Weight on the rear axle of the trailer (em^r)	float	18,47	kg

Field	Type	Example	Comments
Id truck	char	P380411201	Must be defined in the output trucks file
Id stack	char	P380411201_1	
Stack code	char	A	To be used for display (cf FIGURE 1)
X origin (sx_s^o)	int	0	mm
Y origin (sy_s^o)	int	0	mm
Z origin (sz_s^o)	int	0	mm
X extremity (sx_s^e)	int	1010	mm
Y extremity (sy_s^e)	int	1206	mm
Z extremity (sz_s^e)	int	407	mm

Field	Type	Example	Comments
Item ident	char	00900160_20221201_2314	Must be defined in the input items file
Id truck	char	P380411201	Must be defined in the output trucks file
Id stack	char	P380411201_1	Must be defined in the output stacks file
Item code	char	A1	To be used for display (cf FIGURE 1)
X origin	int	0	mm
Y origin	int	0	mm
Z origin	int	0	mm
X extremity	int	1010	mm
Y extremity	int	1206	mm
Z extremity	int	407	mm

Complex Side Constraints

- Some of the constraints are not just simple, linear formulas

$$ej^e = \frac{\sum_{s \in \widehat{TS}_t} (sx_s^o + \frac{(sx_s^e - sx_s^o)}{2}) \times sm_s}{tm_t}$$

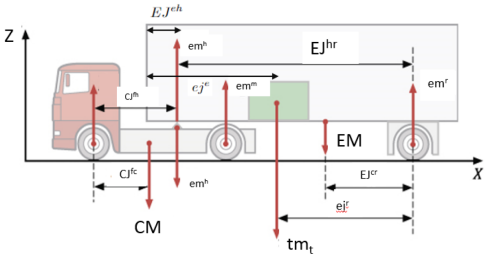
$$ej^r = EJ^{eh} + EJ^{hr} - ej^e$$

$$em^h = \frac{tm_t \times ej^r + EM \times EJ^{cr}}{EJ^{hr}}$$

$$em^r = tm_t + EM - em^h$$

$$em^m = \frac{CM \times CJ^{fc} + em^h \times CJ^{fh}}{CJ^{fm}}$$

- Interpretation requires detailed physical model



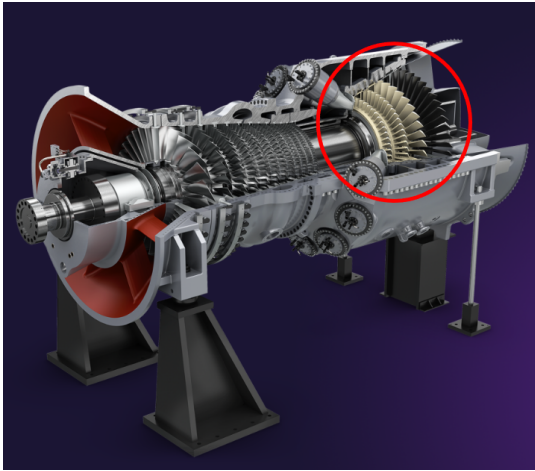
A Grand Challenge for Constraint Acquisition

- Can you extract a transferable model of this problem?
  - Given the data and solutions of all problem instances
- Not too hard to find packing constraints for pieces
- Packing constraints for stacks are simple
- Real problem
  - How many stacks are needed?
  - How many trucks are needed?
  - Many non-trivial side constraints!
- Previous competitions provide similar challenges
  - There is a checker!
  - Lots of instances
  - Solutions not known until challenge end

An Industrial Example

- ASSISTANT 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

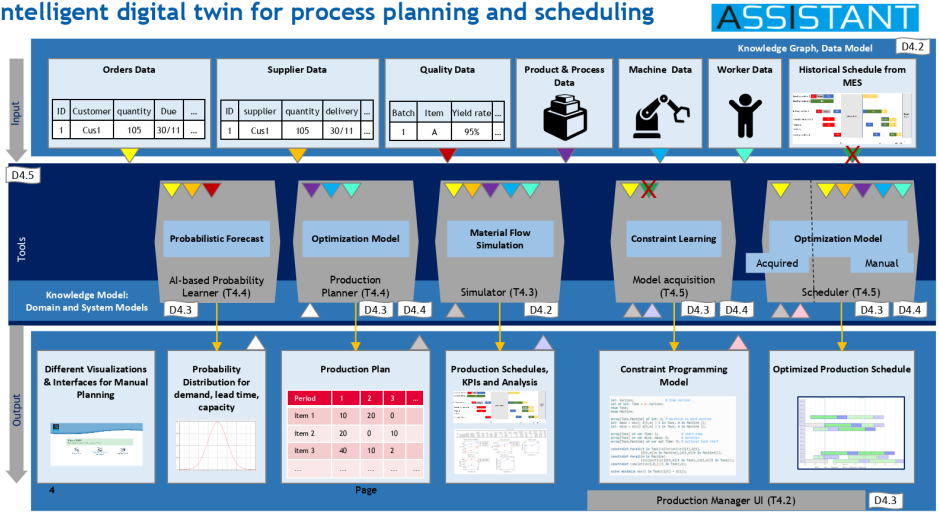


Use Case Scenarios

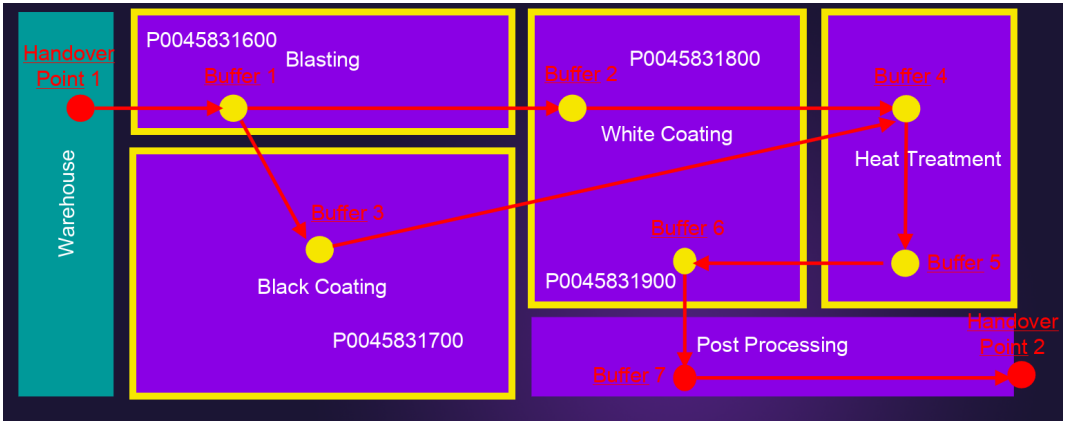
- Schedule *validation* of gas turbine blades and vanes manufacturing operations in Berlin plant
- Schedule *optimization* to manage short-term, mid-term and long-term load fluctuations
- Generate *Make-or-Buy proposals* for workload balancing within the manufacturing network

Digital Twin

Intelligent digital twin for process planning and scheduling



SE Product Routing



Datasets

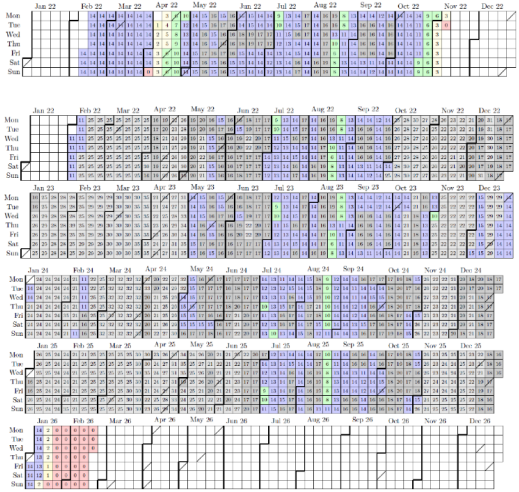
Full Scale Datasets

Berlin06: 96 orders, 9 months horizon, previous review

Berlin07: 450 orders, 4 years horizon

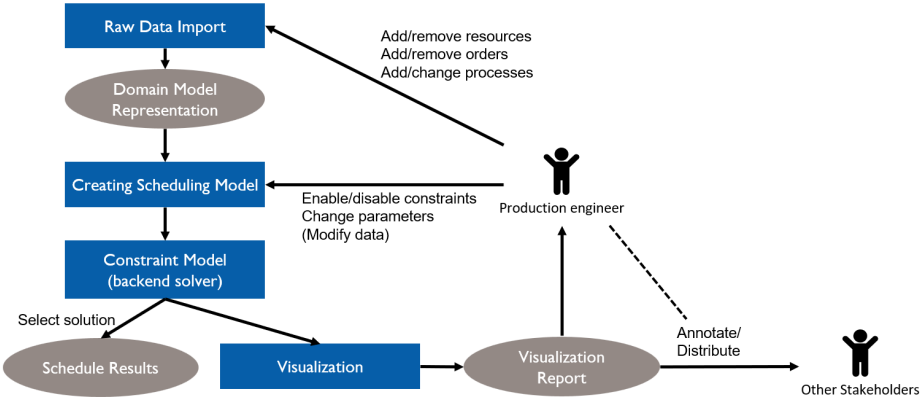
Berlin08: 559 orders, Christmas gap added

Berlin08a: 670 orders, filling gaps



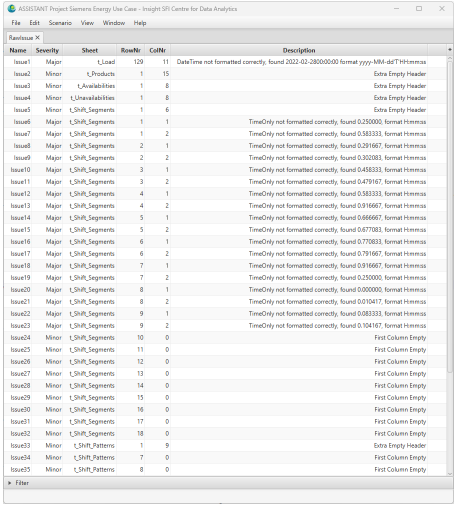
Value in cell indicates active orders
Yellow and red colors indicate low order volume

Optimizer High Level Structure

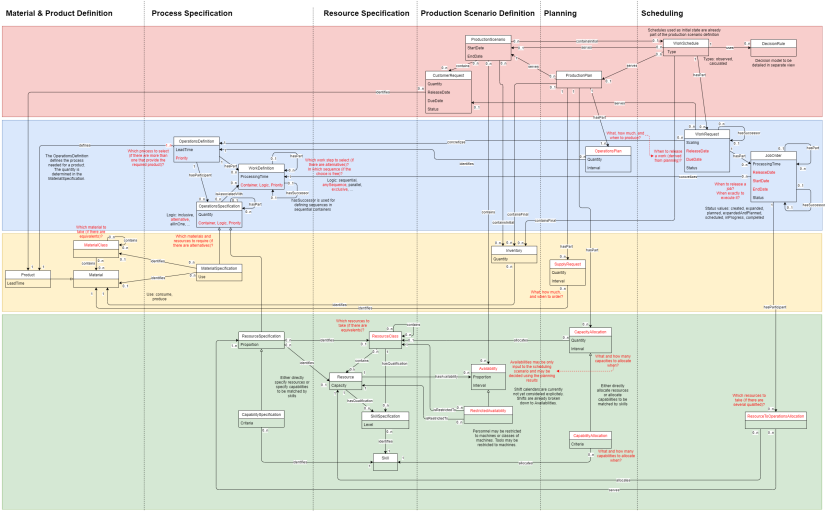


Raw Data - Manual Data Entry Causes Problems

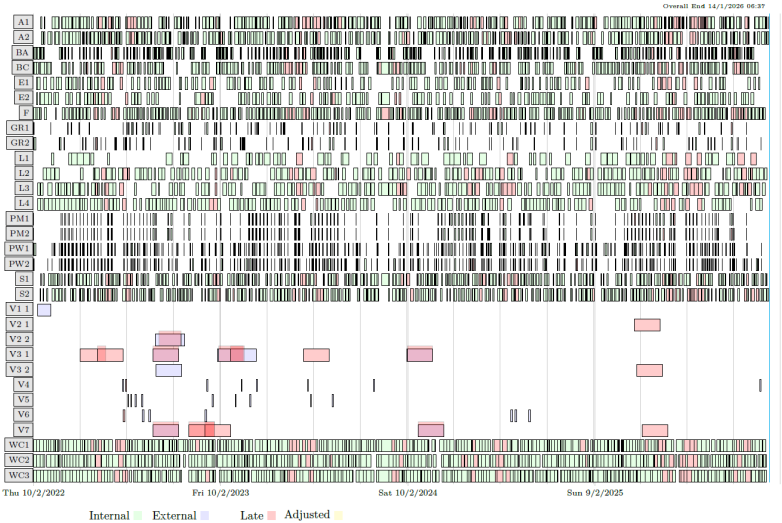
- Raw data come from spreadsheet
  - 20 tabs
- Excel is a particularly bad input data format
- Realistic, not real data
- Created by hand/automatically from existing test scenarios
- Series of files Berlin01 - Berlin05 were too inconsistent to run
- Berlin06 still contains some errors
- Optimizer explains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



Domain Model - Knowledge Graph



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



Challenges for CA

- Input data not fully consistent
- Decide what to do with detected problems
- Solution only shows active part of schedule
- Large set of optional tasks not visible as not active
- Input data contain many fields which are irrelevant for scheduler
  - Component level information
  - Nomenclature
- Many task properties are computed from input data
  - Understand links between multiple objects
  - Time resolution/rounding

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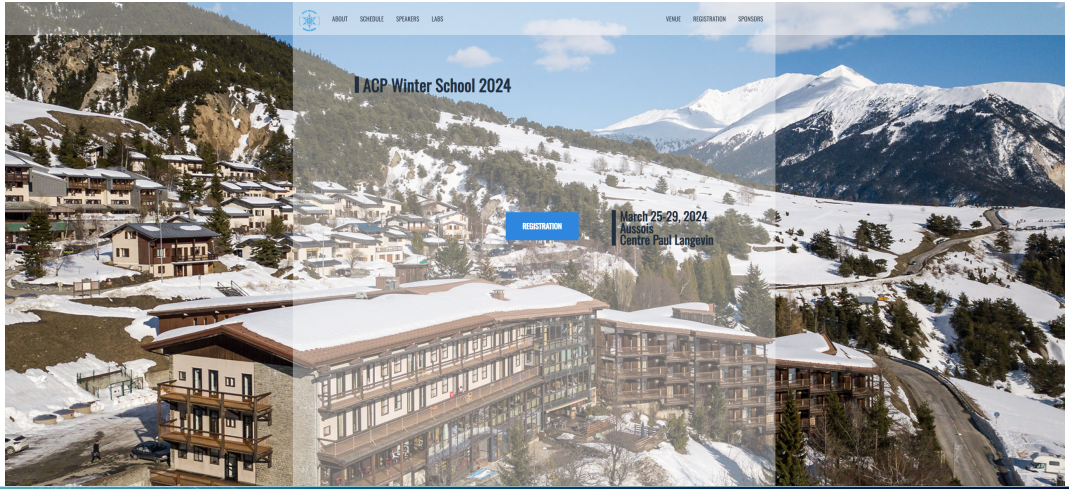
Summary

- Presented different sources for CA benchmarks from simple to complex
- Few sources present all elements required for CA
- Benchmarks rather than competition
- Why data format is important
- As authors, please provide data, solutions, checkers
- Algorithms are necessary, but not sufficient for Constraint Acquisition

Ad: ACP Winter School 2024

- March 25-29, Aussois, France, `https://school.a4cp.org/winter2024/`



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