



# Constraint Based Scheduling: A User Perspective

<http://schedulingseminar.com>

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# Acknowledgments



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Part of this work is based on research conducted within the ASSISTANT European project, under the framework program Horizon 2020, ICT-38-2020, Artificial intelligence for manufacturing, grant agreement number 101000165.

# Key Points



- I'm no longer involved in CP solver development
  - User, not developer perspective
- I want to use off-the-shelf components
  - My project timelines typically are quite tight
- Development of solutions, not technology
- We need more than just a scheduling engine

# Overview of Lecture



- Insight Centre for Data Analytics and ENTIRE
- A Complex Scheduling Solution for Siemens Energy
- Integrated Hospital Resource Management Problem (IHRC 2024)
- A Generic Scheduling Tool
- Survey: Constraint Programming and Scheduling

# Background



- Mathematics @ TH Darmstadt
- 1986-1990 ECRC GmbH, Munich
- 1990-2000, Technical Director, Cosytec SA, Orsay
- 2000-2005, Imperial College London, Parc Technologies Ltd
- 2013-2014, President, Association for Constraint Programming
- Best Application Paper Awards, CP 2009, CP 2013
- Program Chair, CP 2020, CPAIOR 2014
- Distinguished Service Award, ACP, 2022



# Insight is one of the largest data research and innovation centres in Europe...



<b>4</b> <b>Co-Lead Universities</b> 9 partner institutions	Built on <b>20</b> years of research in Data Analytics and AI
<b>450+</b> Academics, Postdocs, PhDs, RAs	<b>3400+</b> Scientific conference and journal papers
<b>175+</b> Funded collaborations with industry partners	<b>350+</b> Research Awards
<b>16</b> Spin out companies 72 license agreements	<b>135+</b> H2020 consortia, 500+ collaborations, 40+ countries
<b>1,137+</b> school visits, 28,000 students	<b>276</b> PhDs graduated



## EDiH – what are they?

A one-stop shops to accelerate digital transformation for enterprise and public sector.

250 EDiHs in the EU

Four EDiHs in Ireland

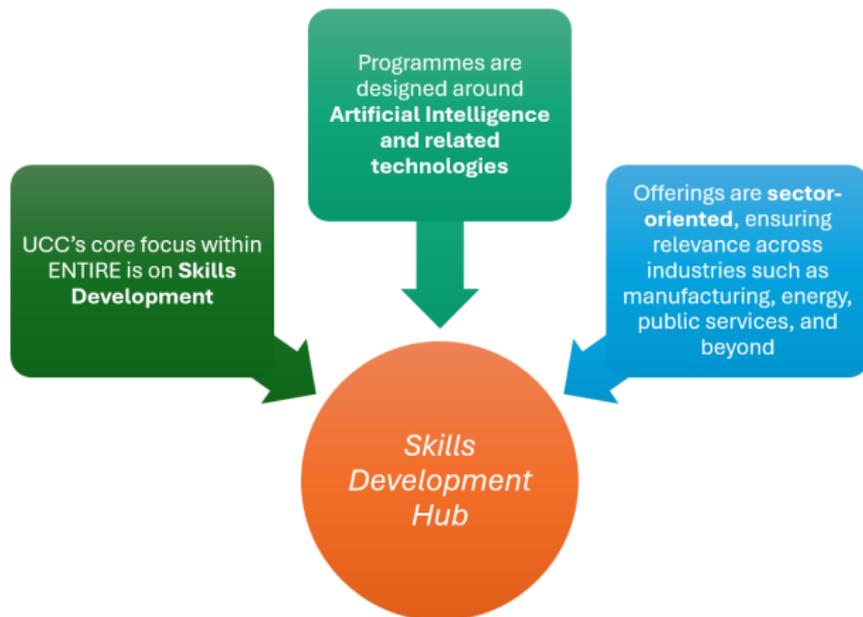
- ENTIRE
- CeADAB
- FactoryXChange
- Data2Sustain

The EDiH logo is displayed in a white box. It consists of the letters "EDiH" in a blue, outlined, sans-serif font.

European  
Digital Innovation  
Hubs Network



<https://entire-edih.ie/>



# Constraint Programming - in a nutshell



- Declarative description of problems with
  - *Variables* which range over (finite) sets of values
  - *Constraints* over subsets of variables which restrict possible value combinations
  - A *solution* is a value assignment which satisfies all constraints
- Constraint propagation/reasoning
  - Removing inconsistent values for variables
  - Detect failure if constraint can not be satisfied
  - Interaction of constraints via shared variables
  - Incomplete
- Search
  - User controlled assignment of values to variables
  - Each step triggers constraint propagation
- Different domains require/allow different methods

# Constraint Programming is Different



- Declarative Programming
  - Concentrate on what you want
  - Not how to get there
  - Program  $\neq$  Algorithm
  - Program = Model
- Applied to Combinatorial Problems
  - No complete polynomial algorithms known (exist?)
  - CP less ad-hoc than heuristics
  - Models can evolve

# A Subtractive Process



*“Oh, bosh, as Mr. Ruskin says. Sculpture, per se, is the simplest thing in the world. All you have to do is to take a big chunk of marble and a hammer and chisel, make up your mind what you are about to create and chip off all the marble you don’t want.”-Paris Gaulois.*

Source: <https://quoteinvestigator.com/2014/06/22/chip-away/>

# Outline



Siemens Energy Case Study (ASSISTANT)

IHTC 2024

A Generic Scheduling Tool

Literature Survey

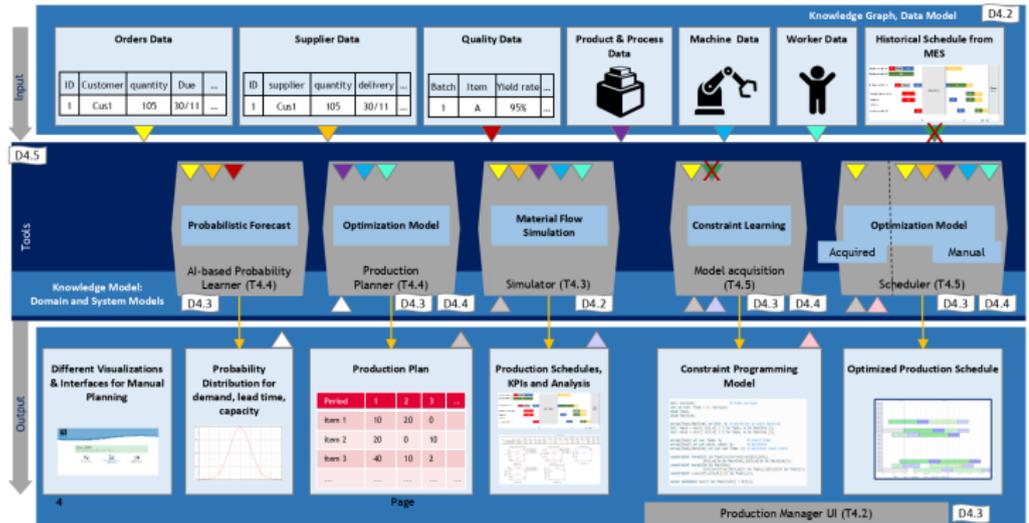
Conclusion

# ASSISTANT Project Overview



Intelligent digital twin for process planning and scheduling

**ASSISTANT**



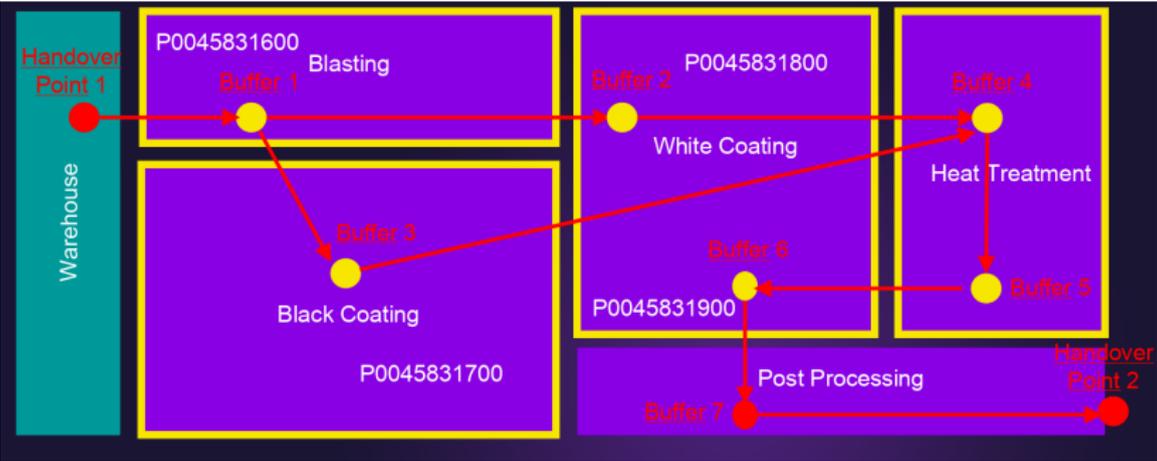
# Assistant Siemens Energy Use Case



## 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

# SE Product Routing



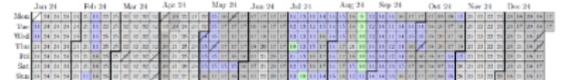
## Full Scale Datasets

Berlin06: 96 orders, 9 months horizon, previous review

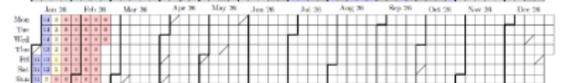
Berlin07: 450 orders, 4 years horizon

Berlin08: 559 orders, Christmas gap added

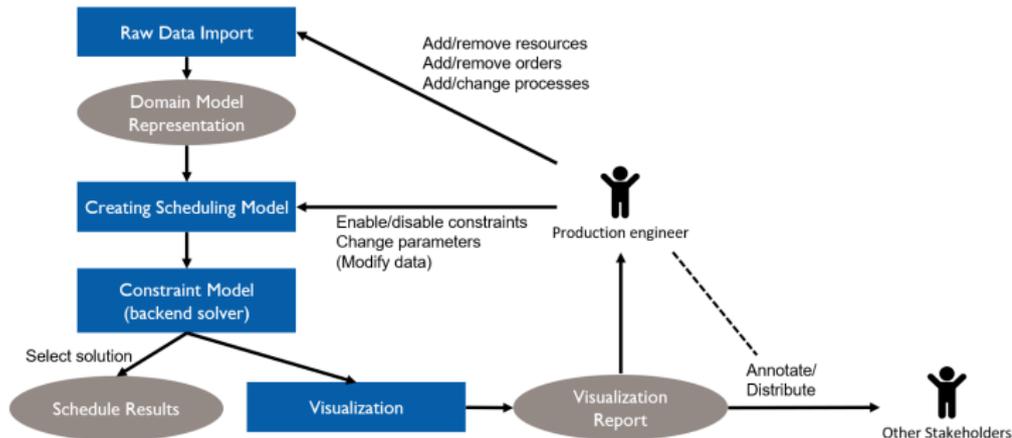
Berlin08a: 670 orders, filling gaps



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

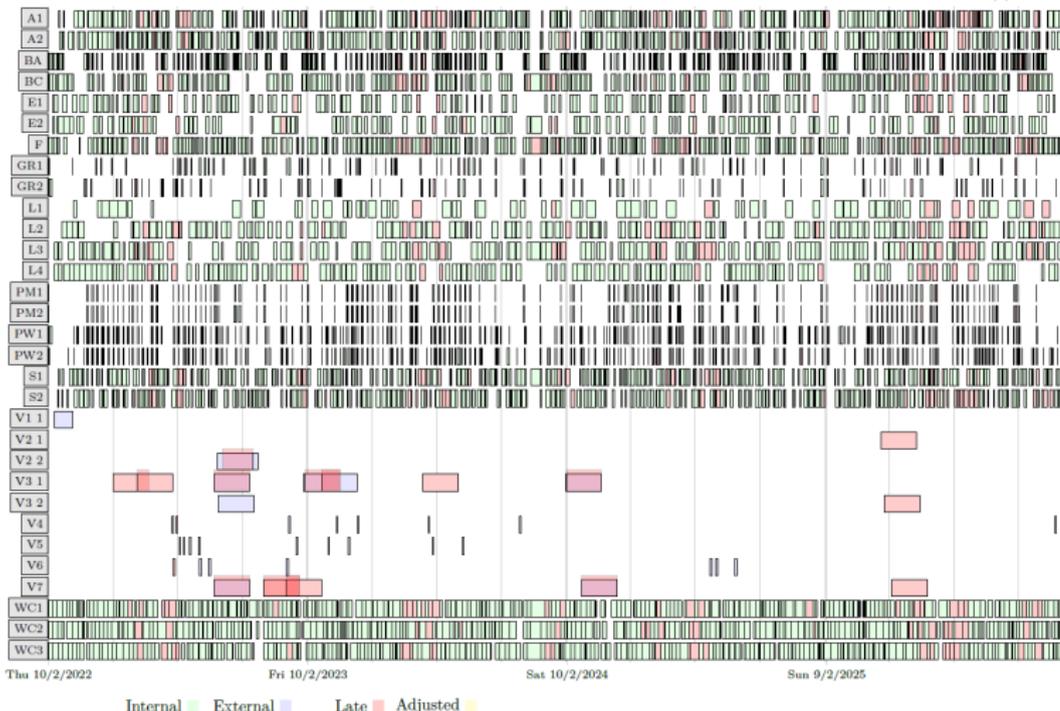
Name	Identity	Sheet	Feeds	Cells	Description
Issue1	Major	L_Load	108	11	Data File not formatted correctly. Issue1(2010-02-08)000100 format yyyy-MM-dd'T'HH:mm:ss
Issue2	Minor	L_Schedule	1	10	Extra Empty Header
Issue3	Minor	L_Weatherfiles	1	6	Extra Empty Header
Issue4	Minor	L_Weatherfiles	1	6	Extra Empty Header
Issue5	Minor	L_01H_Segments	1	6	Extra Empty Header
Issue6	Major	L_01H_Segments	1	1	TimeOnly not formatted correctly. Issue6(12/26/08). Format Problem
Issue7	Major	L_01H_Segments	1	2	TimeOnly not formatted correctly. Issue7(10/01/02). Format Problem
Issue8	Major	L_01H_Segments	2	1	TimeOnly not formatted correctly. Issue8(12/24/02). Format Problem
Issue9	Major	L_01H_Segments	2	2	TimeOnly not formatted correctly. Issue9(10/20/08). Format Problem
Issue10	Major	L_01H_Segments	2	1	TimeOnly not formatted correctly. Issue10(05/01/02). Format Problem
Issue11	Major	L_01H_Segments	2	2	TimeOnly not formatted correctly. Issue11(07/01/02). Format Problem
Issue12	Major	L_01H_Segments	4	1	TimeOnly not formatted correctly. Issue12(08/01/02). Format Problem
Issue13	Major	L_01H_Segments	4	2	TimeOnly not formatted correctly. Issue13(01/02/02). Format Problem
Issue14	Major	L_01H_Segments	5	1	TimeOnly not formatted correctly. Issue14(08/08/02). Format Problem
Issue15	Major	L_01H_Segments	5	2	TimeOnly not formatted correctly. Issue15(07/01/02). Format Problem
Issue16	Major	L_01H_Segments	6	1	TimeOnly not formatted correctly. Issue16(17/01/02). Format Problem
Issue17	Major	L_01H_Segments	6	2	TimeOnly not formatted correctly. Issue17(01/01/02). Format Problem
Issue18	Major	L_01H_Segments	7	1	TimeOnly not formatted correctly. Issue18(01/01/02). Format Problem
Issue19	Major	L_01H_Segments	7	2	TimeOnly not formatted correctly. Issue19(12/26/08). Format Problem
Issue20	Major	L_01H_Segments	8	1	TimeOnly not formatted correctly. Issue20(08/01/02). Format Problem
Issue21	Major	L_01H_Segments	8	2	TimeOnly not formatted correctly. Issue21(01/04/07). Format Problem
Issue22	Major	L_01H_Segments	8	1	TimeOnly not formatted correctly. Issue22(08/01/02). Format Problem
Issue23	Major	L_01H_Segments	8	2	TimeOnly not formatted correctly. Issue23(01/01/07). Format Problem
Issue24	Minor	L_01H_Segments	9	0	First Column Empty
Issue25	Minor	L_01H_Segments	11	0	First Column Empty
Issue26	Minor	L_01H_Segments	12	0	First Column Empty
Issue27	Minor	L_01H_Segments	13	0	First Column Empty
Issue28	Minor	L_01H_Segments	14	0	First Column Empty
Issue29	Minor	L_01H_Segments	15	0	First Column Empty
Issue30	Minor	L_01H_Segments	16	0	First Column Empty
Issue31	Minor	L_01H_Segments	17	0	First Column Empty
Issue32	Minor	L_01H_Segments	18	0	First Column Empty
Issue33	Minor	L_01H_Parameters	1	0	Extra Empty Header
Issue34	Minor	L_01H_Parameters	7	0	First Column Empty
Issue35	Minor	L_01H_Parameters	8	0	First Column Empty



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



Overall End 14/1/2025 06:37



# Implementation

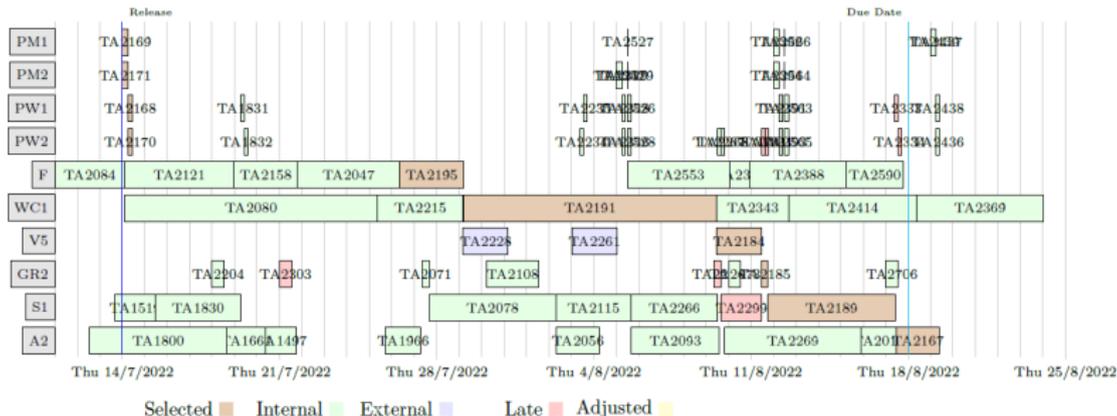


- Requirement capture done inside project
- Data checking/cleaning most time consuming aspect
- Some specified functionality was rejected by Betriebsrat
- Built in Java
- Uses IBM's CPOptimizer back-end
  - Logical choice based on required features
  - Choice created issues later in project
- 120k LoC, 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

# Advanced Feature: Explaining Late Delivery



- Explain why some orders are delivered late
- Find root-cause, show schedule in context



# Evaluation - KPIs

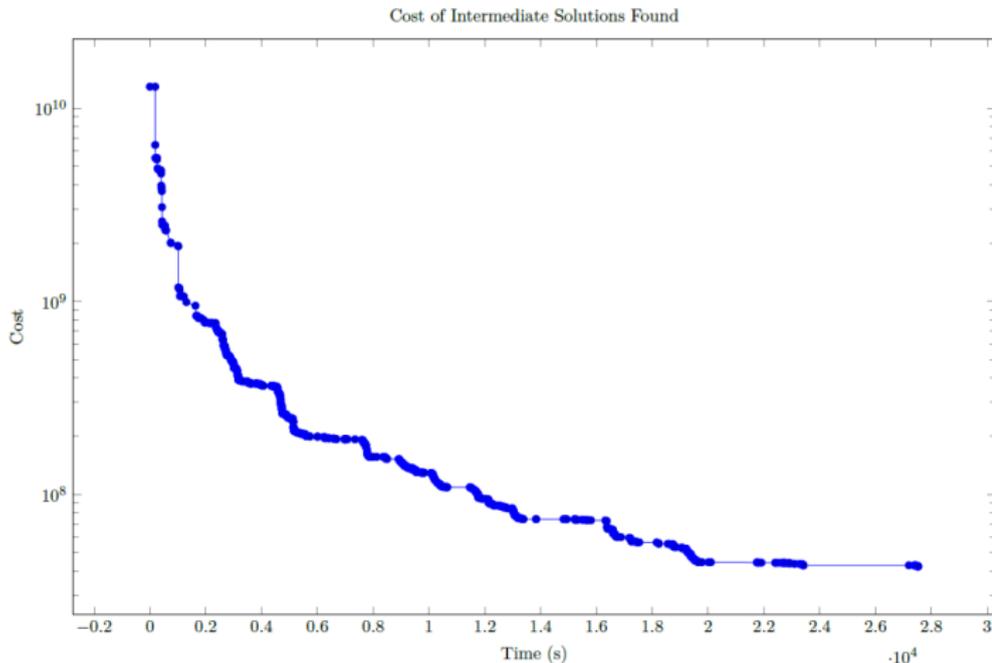


KPI	Baseline	Optimizer
OTD (On-time delivery)	> 80 %	92 %
Bottleneck machine utilization	99.5 %	100 %
Manufacturing defects	10-15 %	< 10 %
Scenarios in 8 hours	15-20	> 100,000

# CPO Keeps on Trucking



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



# Conclusion by Siemens Energy



*“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.”*

from ASSISTANT final project review: Siemens Energy assessment

# Outline



Siemens Energy Case Study (ASSISTANT)

## IHTC 2024

- IHTC 2024 Competition

- Concepts

- Some Data Analysis

- Decomposition

- Results

- New Use Cases

A Generic Scheduling Tool

Literature Survey

Conclusion

# Hospital Capacity Management



- Decide which patients to admit in planning period (2-4 weeks)
- Decide when to admit selected patients
- Surgery performed on day of admission by preassigned surgeon
- Respect capacity constraints of surgeons and theatres
- Assign bed to patient during their stay
- Respect constraints on room capacity and use
- Assign nurses to rooms in each shift to provide required care
- Minimise total, weighted cost



- <https://ihtc2024.github.io/>
- Organized by Udine/Italy and KU Leuven/Belgium
- Under EURO umbrella (replaced Roadef 2024)
- Ran from September 2024 to March 2025
- 32 teams participating
- 70 problem instances



## Participating Teams

We are pleased to share that 32 teams submitted their solvers to the IHTC-2024 competition. We would like to thank all participating teams for their contributions.

After collecting and validating the results, we are pleased to announce the final ranking of IHTC-2024:

Rank	Team Name	Affiliation	Team members	Solver
1	v777v	independent	Venislav Varbanov	
2	SDU-IMADA	University of Southern Denmark	Ahmad Othman, Marco Chiarandini	<a href="#">github</a>
3	Twente	University of Twente	Daniela Guericke, Rolf van der Hulst, Asal Karimpour, Ieke Schrader, Matthias Walter	
4	ORTEC	independent	Wouter Kool, Lotte Berghman, Martijn van Brink, Charlie Ye, Eva van Rooijen, Judith Mourits, Per Kampman	
5	UGent Mippets	Ghent University	Dries Goossens, David Van Bulck, Samuel Bakker, Karel Devriesere, Lisa Garcia Tercero	

We are also pleased to announce that Team SDU-IMADA is the winner of the open-source software prize.

# Is this a good problem for CP?



- There are good and bad points
- Good
  - Not too messy
  - Problem size not super large
  - Decomposes into well-known sub problem types
- Bad
  - Some constraints are totally soft
  - Overall cost is weighted sum of many factors
  - Time resolution limited

# Concepts



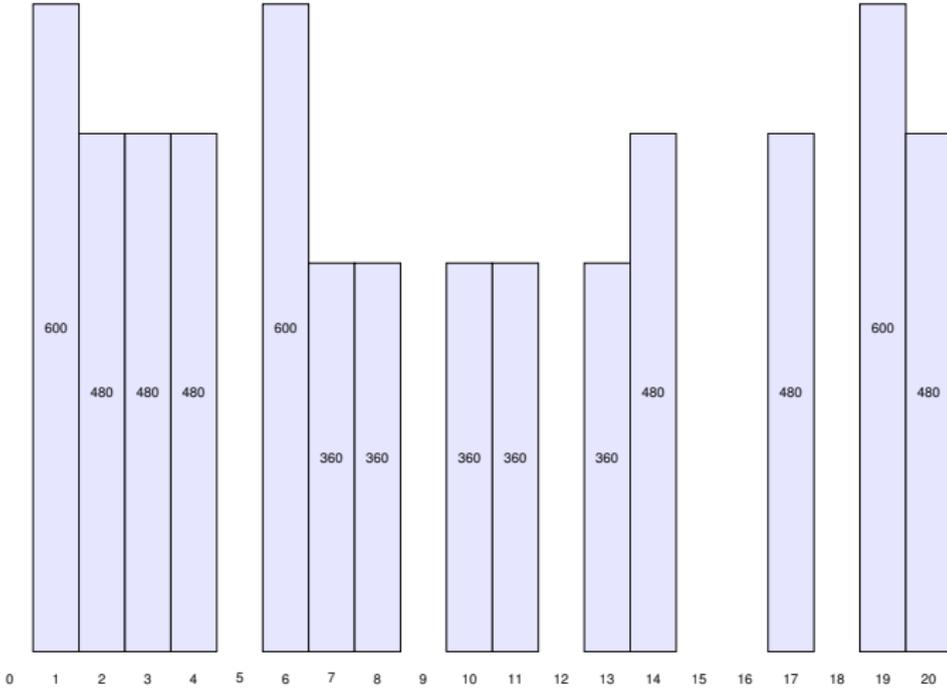
- Time
- Patients/Occupants
- Surgeons
- Nurses
- Operating theatres
- Rooms/beds

# Needed Patient Care on Day of Stay, Top 20 Patients in test10



	0E	0L	0N	1E	1L	1N	2E	2L	2N	3E	3L	3N	4E	4L	4N	5E	5L	5N	6E	6L	6N	7E	7L	7N	8E	8L	8N	9E	9L	9N
p301	3	3	1	2	3	1	2	2	1	2	3	2	3	2	2	2	3	1	2	2	2	3	3	1	3	2	1	3	2	
p121	2	2	2	2	3	2	2	3	1	2	3	2	3	3	2	3	2	1	2	2	2	3	2	1	3	2	1	2	2	
p227	2	2	1	2	2	1	3	2	1	2	3	1	3	2	2	3	3	2	2	3	1	3	2	1	2	3	1	3	2	
p421	2	2	1	3	3	2	2	2	2	2	2	1	2	2	1	2	2	1	3	2	2	3	2	2	3	3	1	3	2	
p042	2	2	2	2	1	2	2	2	2	2	3	1	3	2	2	3	3	1	2	2	2	2	3	1	3	2	2	3	2	
p062	2	3	1	2	2	1	3	2	1	2	2	2	2	3	1	3	2	1	2	2	2	3	2	2	2	3	2	3	1	
p076	3	3	2	2	3	2	3	2	2	2	2	1	2	2	1	2	2	1	2	2	2	3	2	1	2	2	2	3	2	
p081	2	2	1	2	2	2	2	2	1	2	2	1	2	2	2	2	2	1	1	3	1	1	1	1	2	2	1	1	2	
p181	3	3	2	2	3	1	2	2	2	2	2	1	2	2	1	2	2	2	2	2	2	1	3	3	1	2	2	1	2	3
p317	2	2	2	3	3	1	2	2	2	2	2	1	3	2	2	2	2	2	3	2	2	2	3	1	3	2	2	3	3	
p415	3	3	1	3	2	2	2	3	2	2	2	2	3	2	1	2	2	1	2	2	1	2	2	1	3	1	1	2	1	
p149	3	2	2	3	3	2	2	2	2	3	2	1	2	2	2	3	3	2	2	2	1	3	2	2	2	2	2	3	2	
p229	3	2	2	3	2	2	2	3	2	2	2	1	2	3	1	3	3	2	3	2	2	2	2	1	3	3	2	3	2	
p097	3	2	2	3	2	2	2	2	2	3	2	1	2	2	2	2	2	1	3	2	1	2	3	2	2	3	2	2	2	
p104	2	2	1	2	2	1	2	2	2	2	3	1	2	3	1	2	2	2	2	3	2	2	2	2	3	1	1	1	1	
p122	2	3	2	2	2	1	3	2	2	3	2	1	3	2	1	2	2	1	2	2	1	2	3	1	2	3	2	2	2	
p136	3	2	2	2	2	2	2	3	2	2	3	2	2	2	2	2	2	2	2	2	1	2	2	2	1	2	2	2	2	
p190	3	2	2	3	2	2	2	2	1	3	2	1	2	2	1	3	2	2	3	1	1	2	1	2	1	1	1	2	1	
p206	2	3	1	3	2	2	2	2	2	2	2	2	2	2	1	2	2	1	2	3	2	3	3	2	3	2	1	1	1	
p224	3	3	2	2	2	1	2	3	2	3	3	2	3	2	2	3	2	2	3	1	1	3	1	1	1	1	1	2	2	

# Surgeon S5 Availability - test10



# Nurse Roster (Part I) - test10



	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
n000	L	L	N		E	L	N		E	L	N	N	N	N	N	N	N		E		E
n001	L	L	L	L	L	L		E	L	L	L	L	L	L	L	L	E	E		E	E
n002	E		E	L	L	L	L	N	N	N		E		E	E	E	L		E	E	E
n003	N	N		E	L	N	N		E	E	N		E	E	L	N		L	L		E
n004	L	L	L	N	N	N	N		L	L	N	N	N	N		L	L	L	L	L	N
n005	L	L	L	N	N		L	N		N		L	L		L	L	L	L	N	N	N
n006	E	E	L	L	L	N	N		E	E	L		E	N		E	E	E	E	E	E
n007	L	L	N		E	E	E	E	E	L	L		E	E	N	N	N	N	N		E
n008	L	L	L	N		E	L	L	L		L	L	L	N	N	N		L		L	L
n009	N	N	N		E	L	L	L	L		E	L	L	L	N	N	N		N		E
n010	L	N		E	L	L	L	N		L	N	N	N		E	E		E	E	E	L
n011	N	N		E	E	E	L	L	L	L	N		E	E	E	E	L	L	L		E
n012	L	N		E	E	E	E	E	N			E	L	L		E	E	L	N	N	N
n013	L	N		E	L	L	L		E	L	L	L	L	L	L		E	N	N		E
n014	L	N	N		L	N		E	E	L	L	L	N	N		E	E		E	L	L
n015	N	N	N		L	L	L	L	N	N		E	L	L	L	L		E	E	L	L
n016	N	N	N		N		E	E	E	L	L	L	L	N	N		E	E	E	L	N
n017	N	N	N	N		E	N		E	L	N	N		N	N	N	N	N	N		N
n018	L		L	L	N		E	E	N	N	N		L	L	L	L	L	N		L	L
n019	L	L	L	L	L	L	L	L	L	L		E	L	L	L	N	N		E	E	L
n020	L	L	L	N	N		E	E	E	E	E	E	E	L	L	L	L	L		L	L
n021	L	N	N	N		E	E	L	N	N	N	N	N	N		L	N	N	N		E
n022	L	L	L	L	N		E	E	L	N		E	E	E	E	N	N		E	E	E
n023	L	L	L	N	N	N	N		E	N	N	N		E	E	E	E	E	L	N	N
n024	N	N	N	N		E	E	E	E	E	E	E	E	L	L	L	L	L	L	L	L

# Weight Factors



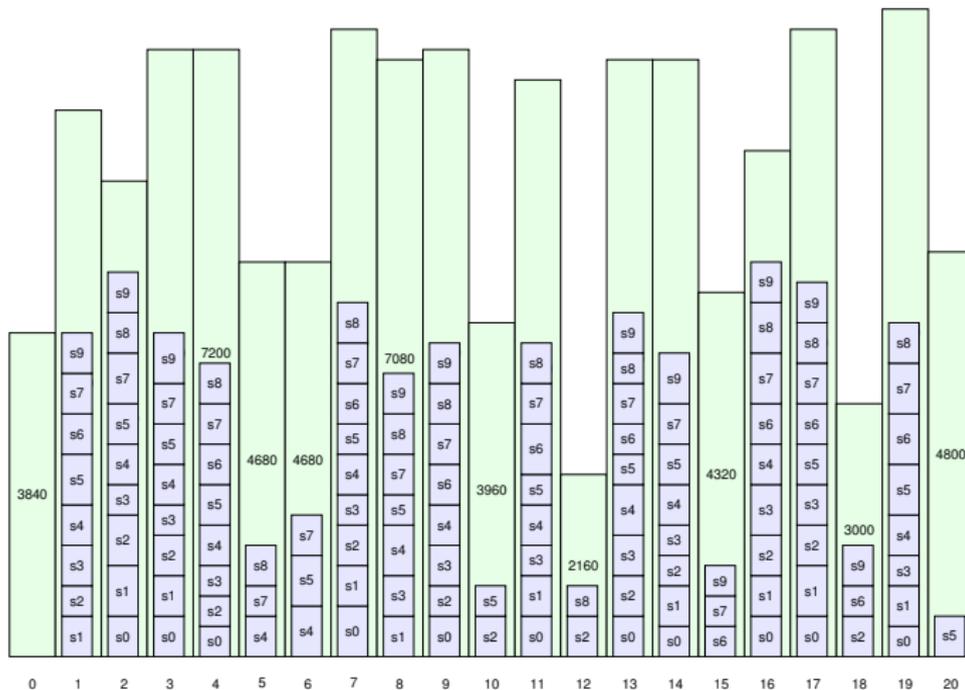
- $w_U$  cost of an unscheduled optional patient, i.e. the patient is not admitted in the planning period
- $w_l$  cost of delay per day for admitting a patient after their release date
- $w_t$  cost of opening a operating theatre for one day
- $w_S$  cost of each additional theatre if a surgeon is allocated to more than one theatre per day
- $w_w$  cost of a workload excess for a nurse in one shift per workload unit
- $w_k$  cost of skill excess for a nurse in one shift per skill unit
- $w_a$  cost of a age group conflict between two patients in the same room per day
- $w_C$  cost of continuity of care excess if multiple nurses are responsible for a patient

# Instance Data

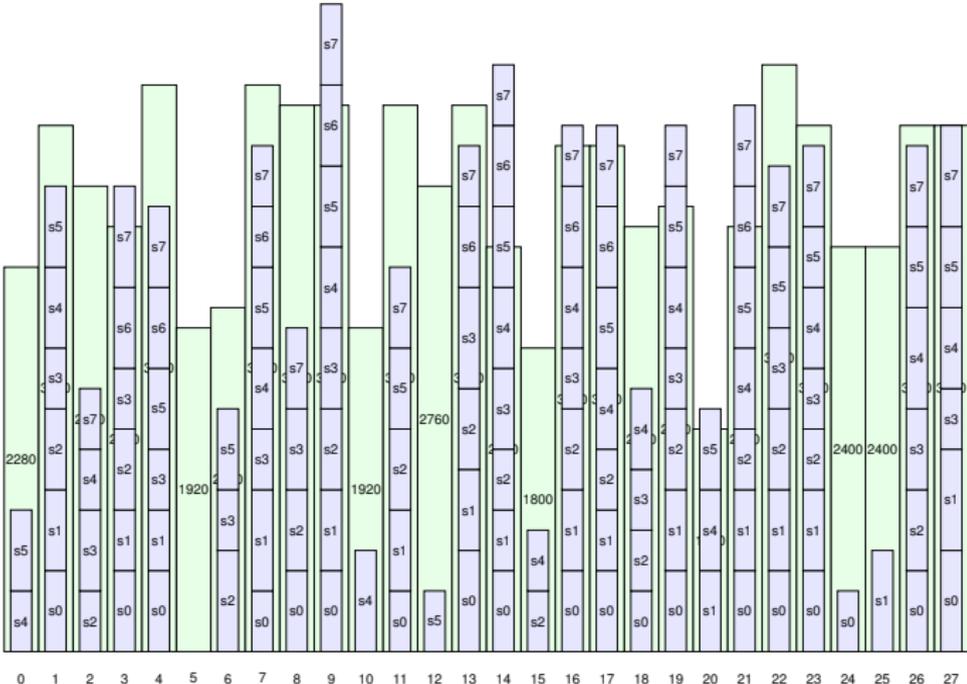


Name	Day	Skill Level	Shift Type	Age Group	Occ	Pat	Mand Pat	Room	Bed	Thea	Surg	Nurse
test01	21	3	3	3	7	42	11	5	13	2	1	13
test02	14	3	3	3	5	37	12	6	16	3	2	17
test03	14	3	3	3	10	45	12	6	20	2	1	14
test04	14	3	3	3	7	54	32	8	25	3	2	19
test05	14	3	3	3	9	62	19	6	19	2	1	15
test06	14	2	3	2	9	111	50	9	22	3	3	20
test07	21	5	3	5	13	113	55	9	26	3	2	22
test08	21	2	3	4	15	173	39	9	27	3	2	21
test09	21	4	3	2	26	146	88	14	44	2	2	29
test10	21	5	3	3	50	525	349	46	130	11	10	83
m21	14	3	3	3	13	234	32	21	59	11	9	46
m22	14	2	3	4	36	244	119	30	89	9	7	62
m23	14	2	3	3	61	254	71	38	117	14	10	77
m24	21	4	3	3	59	397	264	39	115	11	8	78
m25	21	2	3	2	32	412	25	26	75	6	7	54
m26	28	4	3	5	38	570	247	41	125	6	6	81
m27	14	5	3	5	47	295	87	36	112	16	11	70
m28	28	2	3	2	36	611	420	42	124	11	10	84
m29	28	4	3	5	44	631	110	49	144	5	8	96
m30	21	4	3	4	31	489	267	48	140	8	11	90

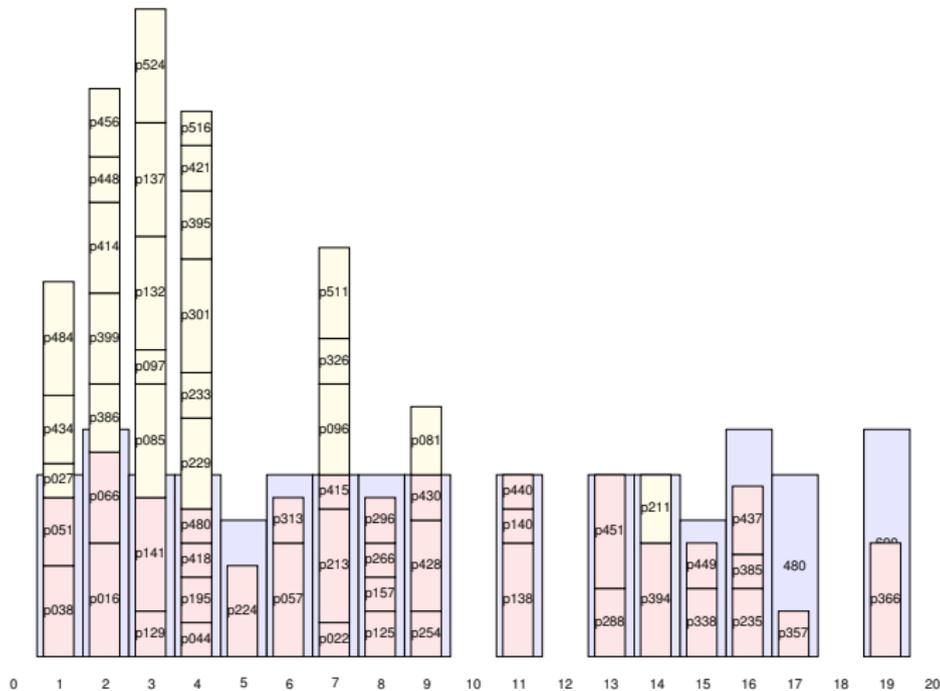
# Total Theatre and Surgeon Capacity - test10



# Total Theatre and Surgeon Capacity - m29



# Capacity and Demand for Surgeon s7 - test10

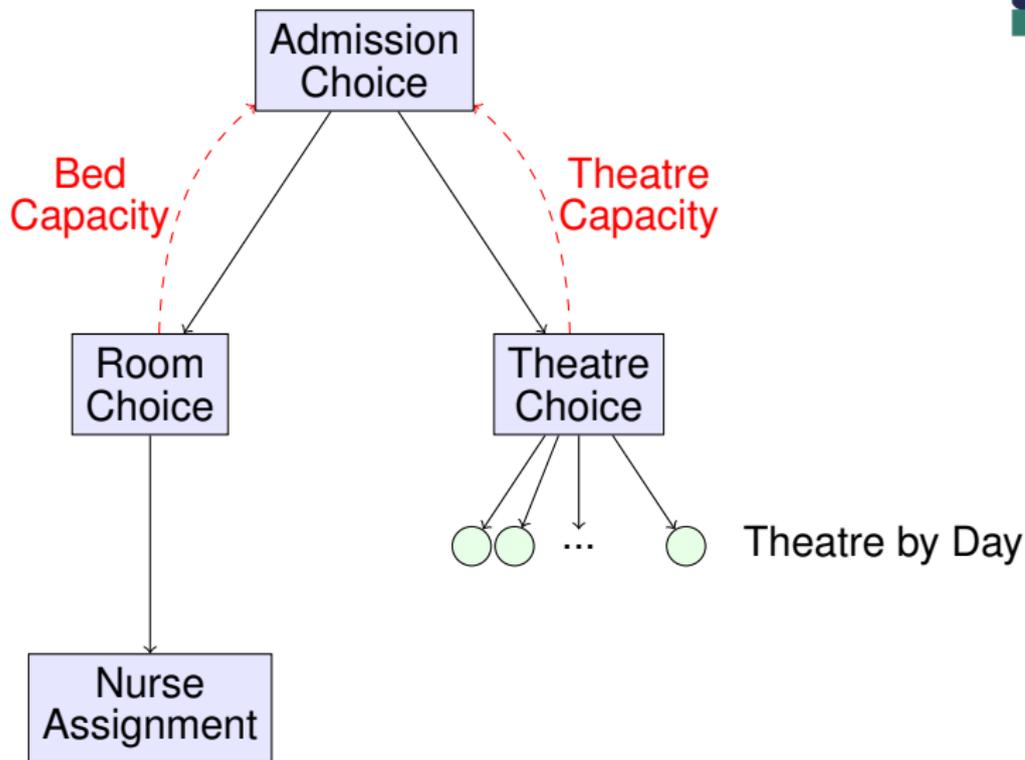


# Results of Analysis



- Finding which patients to admit will be the most important choice.
- To utilise the full surgeon capacity, we will have to delay admission of some patients to use the available time slots.
- We do not have to consider the detailed theatre assignment when making the initial admission selection.
- When admitting a patient, we must have a bed for their full stay available. Estimating full capacity is tough.
- We can initially ignore the nurse workload/skill limits, and age mix constraints as well.

# The Resulting Decomposition



# Stages



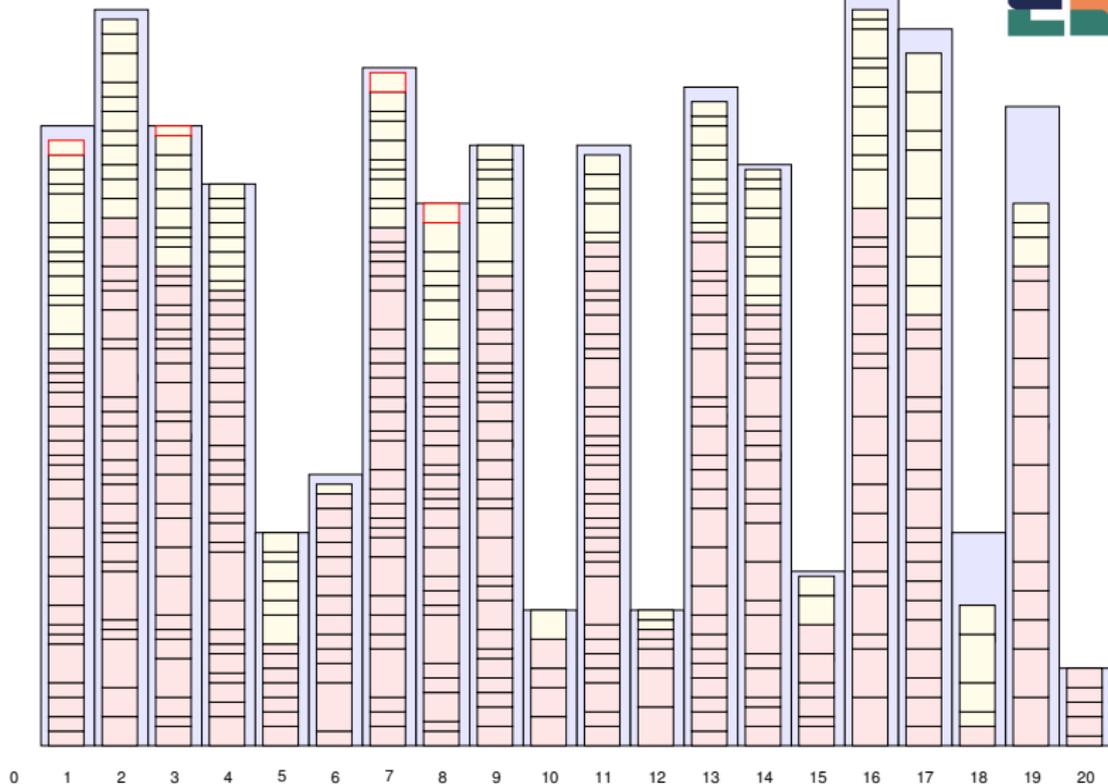
**Admission** decide which patients to admit when

**Room** assign a room/bed to each selected

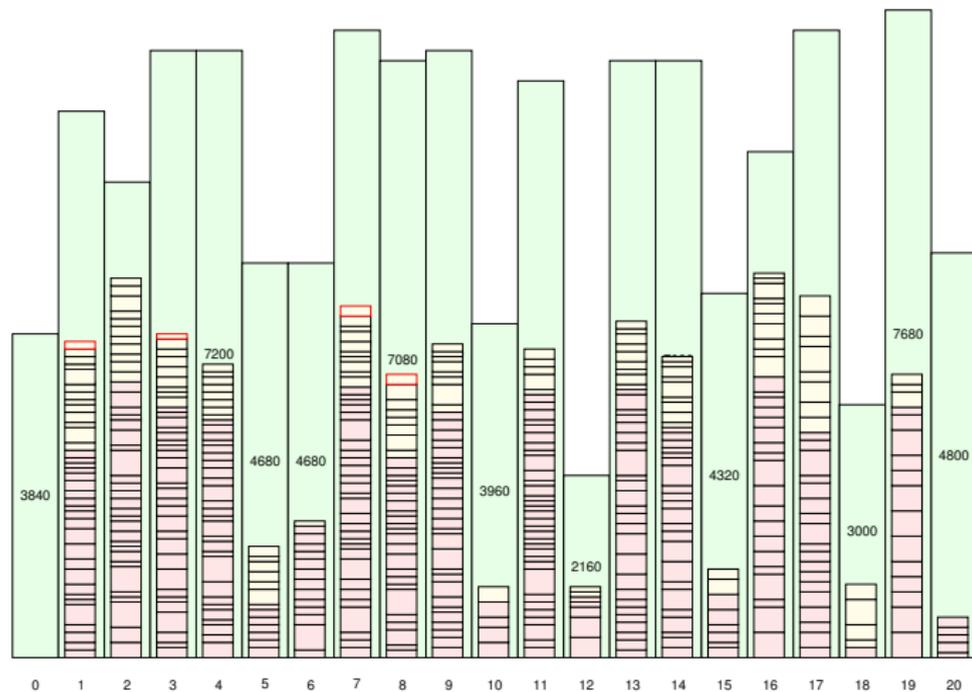
**Theatre** assign a theatre to each patient

**Nurse Assignment** assign a nurse to each (non-empty) room

# Sample solution test10, total surgeon utilisation



# Sample solution test10, total theatre utilisation





- We used this problem in a tutorial on modelling at CP 2025 in Glasgow
- Show different modelling and solution approaches
- Developed in two weeks
- Since then, further improved models for admission
- Split cost into A (admission) and B (nursing)
- Quite good results for cost A, not so good (yet) for cost B

# Cost Comparison A/B



Name	Decomp	Total Cost	Best Cost	Best Gap	Best Gap Percent	Admission Cost	Best Admission Cost	Best Admission Gap	Best Admission Gap Percent	A Cost	Best A Cost	Best A Gap	Best A Gap Percent	B Cost	Best B Cost	Best B Gap	Best B Gap Percent
test01	AR+Td+N	3,210	3,177	33	1.04	1,200	1,200	0	0.00	1,600	2,150	-200	-9.13	1,220	987	233	23.61
test02	AR+Td+N	1,647	1,583	64	4.04	350	350	0	0.00	1,010	1,190	-180	-15.13	637	393	244	62.09
test03	AR+Td+N	10,208	10,184	24	0.24	9,100	9,100	0	0.00	9,435	9,570	-135	-1.41	773	614	159	25.96
test04	AR+Td+N	2,323	2,332	-9	-0.39	250	500	-250	-50.00	1,360	1,740	-380	-21.84	963	592	371	62.67
test05	AR+Td+N	15,030	15,713	-683	-4.35	13,600	14,400	-800	-5.56	14,085	14,545	-460	-5.75	945	768	177	23.02
test06	AR+Td+N	16,811	18,558	-1,747	-9.41	11,000	13,000	-2,000	-15.38	14,570	16,530	-1,960	-11.86	2,241	2,028	213	10.50
test07	A+Rw+Td+N	18,017	17,048	969	5.68	9,750	10,250	-500	-4.88	11,345	12,160	-815	-6.70	6,672	4,888	1,784	36.50
test08	A+Rw+Td+N	22,900	24,947	-1,047	-4.20	20,250	21,000	-750	-3.57	22,500	24,150	-1,650	-6.95	1,400	757	643	84.94
test09	A+Rw+Td+Nd	20,493	20,492	1	0.00	13,300	14,350	-1,050	-7.32	14,850	16,670	-1,820	-10.92	5,643	3,822	1,821	47.65
test10	A+Rw+Td+Nd	61,690	49,444	12,246	24.77	18,300	18,000	300	1.67	29,660	33,380	-3,720	-11.14	32,030	16,064	15,966	99.39
smal001	AR+Td+N	242	0	0	0.00	0	0	0	0.00	180	0	0	0.00	62	0	0	0.00
smal002	AR+Td+N	1,370	0	0	0.00	500	0	0	0.00	1,075	0	0	0.00	265	0	0	0.00
smal003	AR+Td+N	4,102	0	0	0.00	3,000	0	0	0.00	3,325	0	0	0.00	777	0	0	0.00
smal004	AR+Td+N	2,163	0	0	0.00	0	0	0	0.00	1,495	0	0	0.00	668	0	0	0.00
smal005	AR+Td+N	3,545	0	0	0.00	1,750	0	0	0.00	2,830	0	0	0.00	715	0	0	0.00
smal006	AR+Td+N	3,181	0	0	0.00	2,000	0	0	0.00	2,545	0	0	0.00	236	0	0	0.00
smal007	AR+Td+N	3,160	0	0	0.00	800	0	0	0.00	2,090	0	0	0.00	1,070	0	0	0.00
smal008	AR+Td+N	6,814	0	0	0.00	4,500	0	0	0.00	5,055	0	0	0.00	1,759	0	0	0.00
smal009	AR+Td+N	6,815	0	0	0.00	2,000	0	0	0.00	4,200	0	0	0.00	2,615	0	0	0.00
001	AR+Td+N	4,408	3,842	266	6.92	2,800	2,800	0	0.00	3,430	3,510	-80	-2.28	678	332	346	104.22
002	AR+Td+N	1,709	1,264	445	35.21	0	0	0	0.00	725	855	-130	-15.20	984	409	575	140.56
003	AR+Td+N	10,740	10,490	250	2.38	7,600	7,600	0	0.00	9,710	9,725	-15	-0.15	1,030	765	265	34.64
004	AR+Td+N	2,406	0	0	0.00	1,884	522	27.71	0	0	0	0.00	1,240	644	617	95.81	
005	A+Rw+Td+N	13,250	12,790	460	3.84	8,500	8,500	0	0.00	12,400	12,400	0	0.00	850	300	490	130.11
006	AR+Td+N	10,746	10,671	75	0.70	5,900	5,900	0	0.00	10,390	10,390	0	0.00	356	281	75	26.69
007	AR+Td+N	7,096	5,026	2,070	41.19	0	0	0	0.00	1,671	2,201	-530	-24.08	5,425	2,825	2,600	92.04
008	A+Rw+Td+Nd	7,658	6,291	1,367	21.73	200	400	-200	-50.00	4,230	4,180	50	1.20	3,428	2,111	1,317	62.39
009	A+Rw+Td+N	7,718	6,682	1,036	15.50	500	500	0	0.00	Infinity	4,185	3,860	295	7.58	3,533	2,792	280.54
010	A+Rw+Td+N	22,785	20,820	1,965	9.44	12,900	12,600	300	2.38	15,580	15,695	-285	-1.82	6,805	5,125	1,680	32.78
011	A+Rw+Td+Nd	26,148	25,938	210	0.81	24,500	24,500	0	0.00	25,565	25,555	10	0.04	583	383	200	52.22
012	A+Rw+Td+N	15,636	12,430	3,206	25.79	4,800	5,800	-1,000	-17.24	6,855	7,580	-725	-9.56	8,781	4,850	3,931	81.05
013	A+Rw+Td+N	18,503	17,328	1,175	6.78	6,500	5,500	1,000	18.18	14,360	13,655	705	5.16	4,143	3,673	470	12.86
014	A+Rw+Td+Nd	11,226	9,746	1,480	15.16	3,850	3,850	0	0.00	5,809	6,116	-307	-5.02	5,117	3,630	1,487	49.23
015	A+Rw+Td+Nd	15,256	12,486	2,770	22.18	13,500	2,450	700	28.57	7,540	7,645	-405	-5.10	7,716	4,541	3,175	69.92
016	A+Rw+Td+Nd	11,520	10,130	1,381	13.62	4,050	3,600	450	12.50	8,210	7,865	345	4.36	3,310	2,274	1,036	45.56
017	A+Rw+Td+Nd	50,990	40,535	10,455	25.79	15,500	14,000	1,500	10.71	27,055	28,375	-1,320	-4.65	23,935	12,160	11,775	96.83
018	A+Rw+Td+Nd	38,524	37,660	864	2.26	33,300	33,300	0	0.00	36,722	36,702	20	0.05	1,802	958	844	88.10
019	A+Rw+Td+Nd	52,691	44,587	8,014	17.97	14,000	28,750	-14,750	-51.30	32,660	35,985	-3,925	-10.91	20,541	8,602	11,939	138.79

# Which problem do we need to solve?



- Competition is only concerned with generating initial solution
- But there are many more use cases to study
  - What happens if a rejected patient needs the operation now
  - What happens if a surgeon cancels a session
  - What happens if the hospital closes for a disaster event
  - What resources do we need to handle  $k$  additional patients
- This is linked to ongoing work on explanations in our lab

# Outline



Siemens Energy Case Study (ASSISTANT)

IHTC 2024

## A Generic Scheduling Tool

Under the hood

Input Data/ Result Output

Instance Generator

Literature Survey

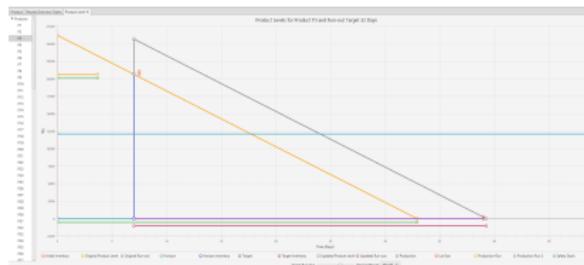
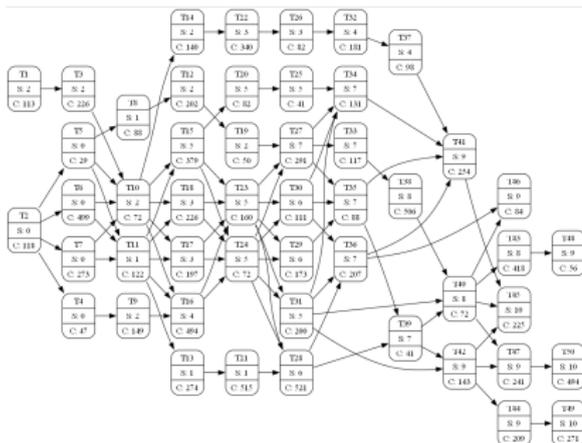
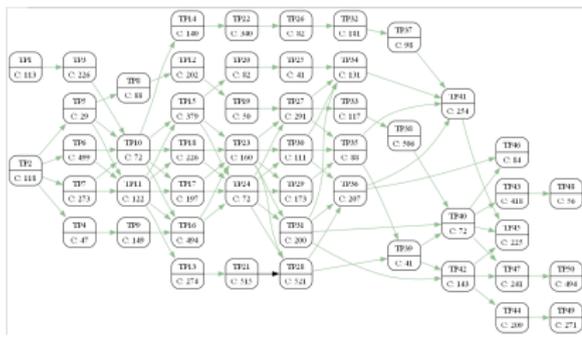
Conclusion

# A Generic Scheduling Tool



- Intended for ENTIRE customers, SME and PSO
  - Smaller problem scope, very limited tech resources
- No programming, configured by JSON input data
- Compositional use of different constraint types
- Different commercial or open-source back-end solvers
- Developed in Java
- Interactive JavaFX front-end
- Can be used as back-end scheduling tool/server (REST)
- Instance generator included
- Readers for multiple benchmark types included

# Scheduling Tool GUI Examples



# Back-end solvers



- Provide both open-source and commercial solver interfaces
- Allow experimentation without having to buy commercial tools straightaway
- Gives a level playing field to compare solvers and models
- Provides out-of-the-box, generic performance

# Google OR-Tools CPSat Solver



- Open-Source tool provided by Google
- Available at `https://developers.google.com/optimization/cp/cp_solver`
- Probably best open-source CP solver for scheduling
- This solver is packaged with scheduling tool

## Example Problem

Below is a simple example of a job shop problem, in which each task is labeled by a pair of numbers  $(m, p)$  where  $m$  is the number of the machine the task must be processed on and  $p$  is the processing time of the task – the amount of time it requires. (The numbering of jobs and machines starts at 0.)

- job 0 =  $\{(0, 3), (1, 2), (2, 2)\}$
- job 1 =  $\{(0, 2), (2, 1), (1, 4)\}$
- job 2 =  $\{(1, 4), (2, 3)\}$

In the example, job 0 has three tasks. The first,  $(0, 3)$ , must be processed on machine 0 in 3 units of time. The second,  $(1, 2)$ , must be processed on machine 1 in 2 units of time, and so on. Altogether, there are eight tasks.

## A solution for the problem

A solution to the job shop problem is an assignment of a start time for each task, which meets the constraints given above. The diagram below shows one possible solution for the problem:



You can check that the tasks for each job are scheduled at non-overlapping time intervals, in the order given by the problem.

The length of this solution is 12, which is the first time when all three jobs are complete. However, as you will see [below](#), this is not the optimal solution to the problem.

(from OR-Tools website)

# CP Optimizer from IBM



- Commercial tool of IBM
- <https://www.ibm.com/products/ilog-cplex-optimization-cplex-cp-optimizer>
- Part of optimization suite with Cplex, OPL
- We allow to interface with it
- Academic licenses available
- Well-known for capabilities for scheduling

## Resources



### Applications of constraint programming

Explore applications of constraint programming including production problem and scheduling use cases.

[Read the documentation](#) →

(from CPOptimizer website)

# MiniZinc from Monash University



- Modelling language and backend tools from Monash University in Melbourne, Australia
- Available from <https://www.minizinc.org/>
- Widely used for teaching
- Allows different backend solver to run from same model
- Generic CP tool, not optimized for scheduling
- Requires separate installation, open-source

A screenshot of the MiniZinc website. The page title is "MiniZinc". Below the title is a brief description: "MiniZinc is a high-level constraint modelling language that allows you to easily express and solve discrete optimisation problems." There are buttons for "Download" and "Windows 10 or later". Below that, it says "Latest release 2.0.7 (2020-09-01)". There are links for "Features", "Source code", and "License information". At the bottom, it says "MiniZinc is developed at Monash University with support from QUTBIA". On the right side of the screenshot is a weekly schedule grid for a person named "Robbing". The grid has columns for Mon, Tue, Wed, Thu, and Fri. The rows list activities: Alice, Mike, Chris, Darby, Ernst, Green, Jason, Kate, Lloyd, Madie, Neah, and Paula. Each cell in the grid contains a time slot (Morning, Afternoon, Evening, Night, Day) and a color-coded box representing the activity. For example, on Monday, Alice has a Night slot, Mike has an Evening slot, and Chris has a Day slot.

(from MiniZinc Website)

# Which Solver is Better?



- We present results on a few benchmark types
- Fair comparison between solvers
  - Same hardware, Windows 11 laptop
  - CPU i7-10875H @ 2.3GHz, 64GB, four cores
  - Same timeout (600 s)
- Not a fair comparison to state-of-the-art
  - Uses out-of-the-box model
  - Significant improvements possible
  - More specific models
  - Parameter tuning
  - Unlimited runtime

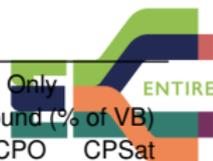
# Taillard Job-Shop Benchmarks



Group	Nr	All Instances				Optimal Only		Non Optimal Only			
		Optimal (% of All Instances)				Time (% of VB)		Cost (% of VB)		Bound (% of VB)	
		Both	CPO	CPSat	None	CPO	CPSat	CPO	CPSat	CPO	CPSat
15/15	10	90.00	0.00	0.00	10.00	105.19	141.18	100.00	100.00	97.17	100.00
20/15	10	20.00	0.00	0.00	80.00	267.27	263.20	100.99	100.05	98.50	99.93
20/20	10	0.00	0.00	0.00	100.00	n/a	n/a	100.74	100.06	97.96	100.00
30/15	10	10.00	0.00	10.00	80.00	174.32	100.00	100.18	100.49	99.87	100.00
30/20	10	0.00	0.00	0.00	100.00	n/a	n/a	100.30	101.30	99.40	100.00
50/15	10	100.00	0.00	0.00	0.00	100.00	685.09	n/a	n/a	n/a	n/a
50/20	10	10.00	60.00	0.00	30.00	100.00	381.38	100.00	101.60	100.00	100.00
100/20	10	10.00	90.00	0.00	0.00	100.00	416.13	100.00	101.73	100.00	66.81

- Significant number of problems solved to optimality in 600s
- In terms of quality, solvers are quite similar
- CPO wins in terms of solution times for larger instances

# Results for Hybrid Flexible Flow-Shop



Group	Nr	All Instances				Optimal Only		Non Optimal Only			
		Optimal (% of All Instances)				Time (% of VB)		Cost (% of VB)		Bound (% of VB)	
		Both	CPO	CPSat	None	CPO	CPSat	CPO	CPSat	CPO	CPSat
20	25	76.00	0.00	20.00	4.00	100.00	580.71	100.00	100.00	96.52	100.00
25	25	80.00	0.00	8.00	12.00	101.65	238.02	100.00	100.37	97.67	100.00
30	25	60.00	0.00	4.00	36.00	100.35	264.69	100.18	101.05	100.00	100.00
40	25	4.00	16.00	0.00	80.00	100.00	2554.03	100.00	104.68	100.00	100.00
50	25	0.00	4.00	0.00	96.00	n/a	n/a	100.00	107.87	100.00	100.00
100	25	0.00	0.00	0.00	100.00	n/a	n/a	100.00	120.43	100.00	100.00
200	25	0.00	0.00	0.00	100.00	n/a	n/a	100.00	188.60	100.00	100.00
300	24	0.00	0.00	0.00	100.00	n/a	n/a	100.00	263.22	100.00	100.00
400	25	0.00	0.00	0.00	100.00	n/a	n/a	100.00	246.34	100.00	100.00

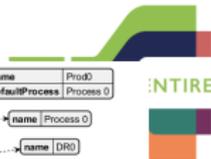
- Only smaller/medium instances solved to optimality
- For those problems, both solvers perform well
- CPO significantly better on large instances
- But: Best CP only result with SICStus Prolog (Armstrong et al, CP 2021)
- Best overall result with NEH/CP hybrid (Garraffa et al, Comput. Oper. Res., 2025)

# General Recommendations



- If you already have access to CPO, use it!
- For new problem types, do an evaluation with CPSat first
- Out of the box, CPO performs more consistently
- May be easier to extend CPSat with your own research
- Use multiple cores and memory to your advantage
- OptalCP (see last talk) gave superb results on Siemens Energy test case

# I/O: JSON Base Data



- Description of
  - Product
  - Process
  - DisjunctiveResource
  - CumulativeNeed
  - ProcessStep
  - ResourceNeed
  - CumulativeProfile
  - Problem
  - CumulativeResource
  - ProcessSequence



# Schedule Input Data



- Description of
  - Downtime
  - Task (x2)
  - Job
  - Order
  - WiP



# Instance Generator



- Application allows to generate different types of test problems
- Different types of resource models
- Different numbers of orders, resources, WiP, downtime
- Useful to generate more life-like examples combining different constraint types

# Instance Generator Dialog



- Resource Model
  - Select a resource model defining the overall structure of problem
- Nr Disjunctive Resources
  - Describe how many disjunctive resources are generated
- Resource Probability
  - The probability that a resource is compatible with a task
  - Only for some resource models

A screenshot of the 'Data Generator Parameters' dialog box. It contains several input fields and sliders. The 'Label' field is empty. The 'StartDate' is set to '01/10/2024' and the 'Start Time' is '0 : 00'. The 'Resource Model' is set to 'HybridFlowShop'. The 'Nr Disjunctive Resources' slider is set to 7. The 'Resource Probability' slider is set to 0.3. The 'Cumulative Resource' section is expanded, showing 'Nr Cumulative Resources' set to 1, 'Cumul Demand Range' set to 1, 'Profile Pieces' set to 3, and 'Cumul Capacity Range' set to 6. There are 'Run' and 'Cancel' buttons at the bottom right.

Data Generator Parameters

Label:

StartDate: 01/10/2024 Start Time: 0 : 00

Resource Model: HybridFlowShop

Nr Disjunctive Resources: 1 3 5 7 9 11 13 15 17 19 20

Resource Probability: 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

► Products

► Duration

▼ Cumulative Resource

Nr Cumulative Resources: 1 2 3 4 5

Cumul Demand Range: 1 2 3 4 5 6 7 8 9 10

Profile Pieces: 1 2 3 4 5

Cumul Capacity Range: 1 6 11 16 21 26 30

► Orders

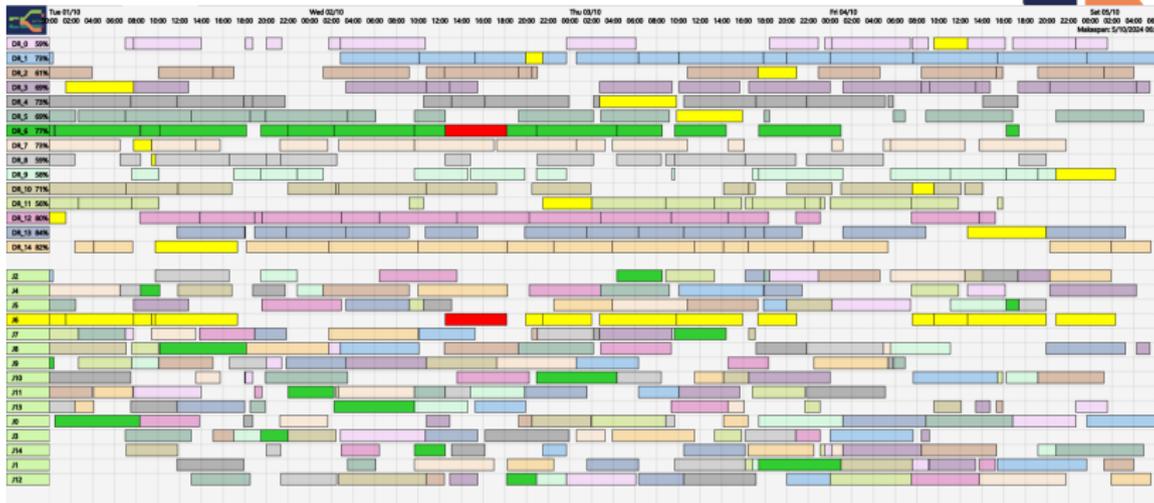
► WIP

► Downtime

► Other Parameters

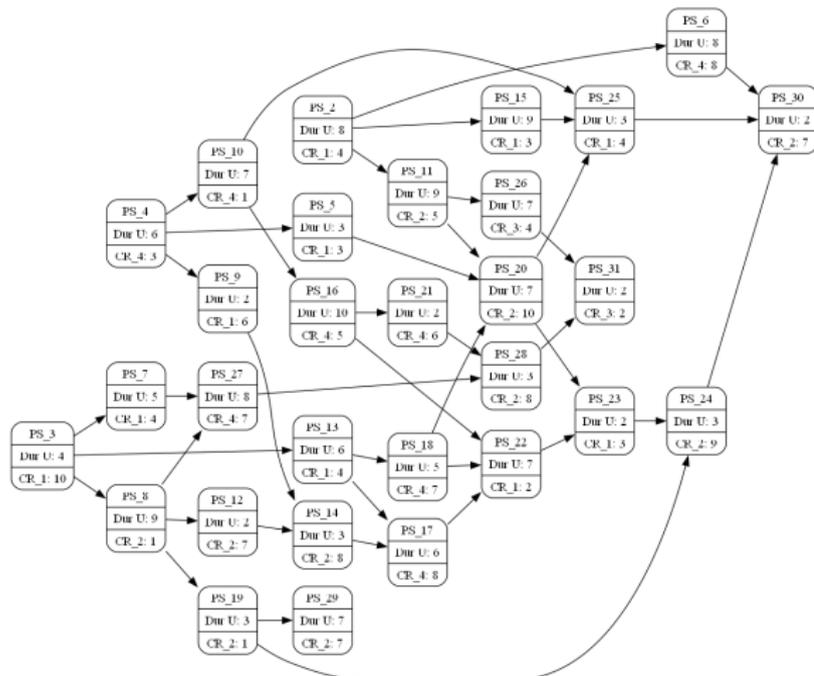
Run Cancel

# GUI: Example Job-Shop Solution



- One task is selected (in red), in both Machine and Job Gantt Chart
- Tasks are colored by machine, note coloring in jobs is different for each job

# GUI: RCPSP Process Diagram



- Multiple sources, sinks
- Multiple cumulative resources

# More on Visualization



- Tutorial at CP 2021  
(<https://cp2021.a4cp.org/tutorials.html>)
- By Helmut Simonis, Insight/UCC and Guido Tack, Monash University
- Video at  
<https://www.youtube.com/watch?v=AI-ZfQtMLAU>

# Take-Away Message



- Visualization can help at different stages of the development process
- Discover problems early
- Understand what is happening without drowning in details
- Easily communicate with stakeholders without CP experience
- Decide how much integration with solver you need
- Complex use cases require visualization to be practical
- Generic vs. application specific visualization

# Outline



Siemens Energy Case Study (ASSISTANT)

IHTC 2024

A Generic Scheduling Tool

Literature Survey

Conclusion

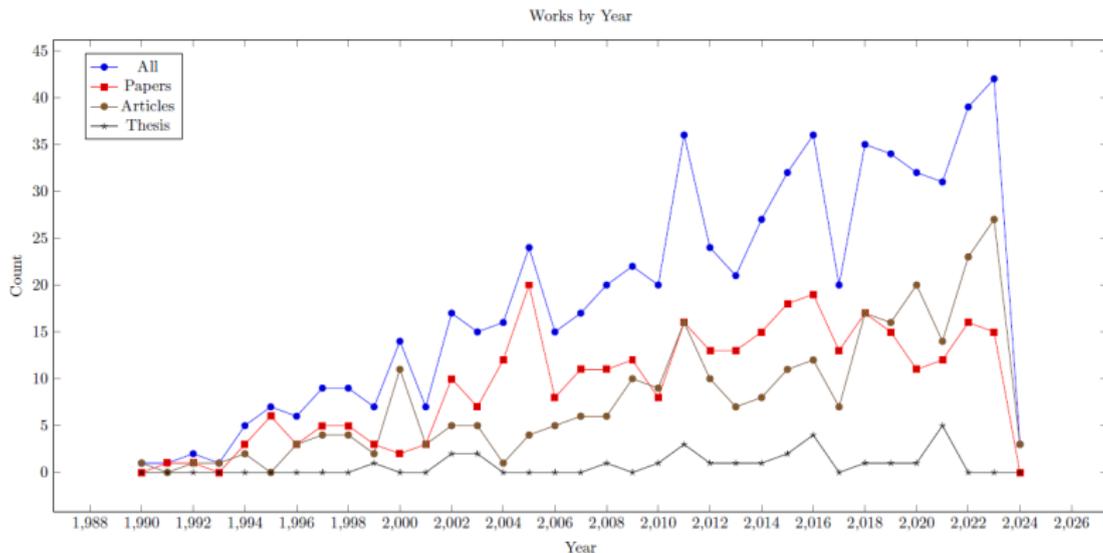
# Constraint Programming and Scheduling - A Survey



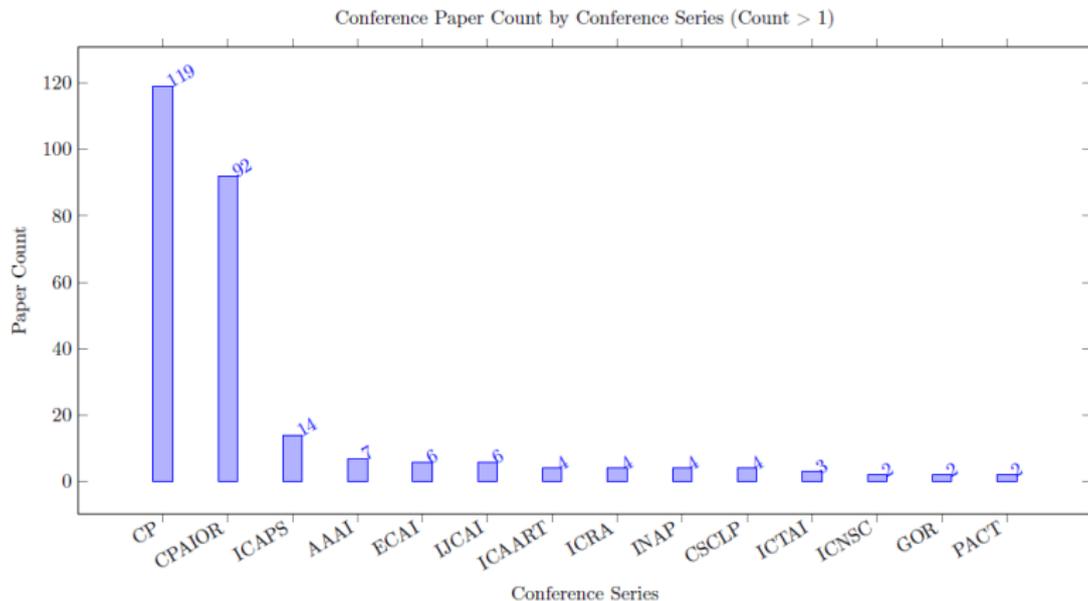
- Joint work with Cemalettin Ozturk, MTU
- What is out there
- Where to start
- Where to publish
- I'm interested in some specific topic, what is relevant
- Results available at

`https://hsimonis.github.io/pthg24/`

# Overall Analysis (Based on 1278 Works)



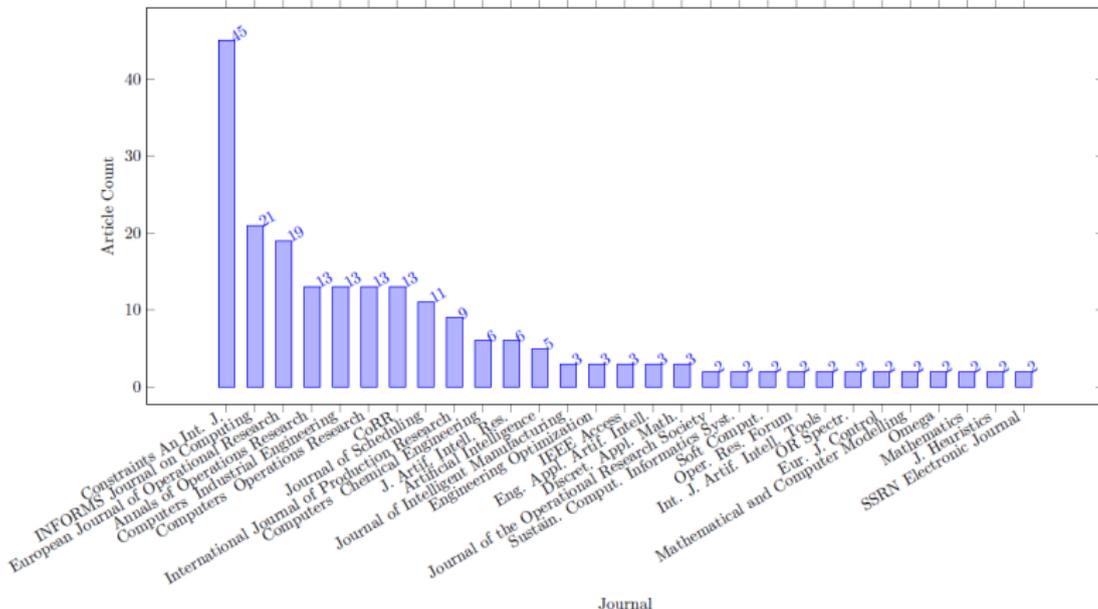
# Origin of Papers



# Origin of Articles



Article Count by Journal (Count > 1)



# 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	e
<a href="#">Laborie03</a> <a href="#">369</a>	38	task, precedence, order, cmax, machine, job, activity, re-scheduling, setup-time, release-date, inventory, preempt, job-shop, resources, scheduling, make-span		cycle, table constraint, cumulative, disjunctive	C++	Ilog Scheduler			benchmark	edge-finding, not-last, energetic reasoning, not-first, time-tabling	1201	1731
<a href="#">LaborieRSV18</a> <a href="#">372</a>	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, petro-chemical industry	real-world, CSPlib, benchmark	edge-finding	1050	1610
<a href="#">LacknerMMWW23</a> <a href="#">374</a>	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	954	1514
<a href="#">LammaMM07</a> <a href="#">377</a>	15	job-shop, resource, scheduling, precedence, order, task, job, distributed, no-wait		cumulative, cycle, bin-packing	C++, Prolog	ECLiPSe, OPL, CHIP	railway		generated instance, Roaddef, benchmark, random instance	energetic reasoning, sweep, edge-finding	1230	1766
<a href="#">LatorCB12</a> <a href="#">385</a>	52	machine, make-span, job, precedence, resources, scheduling, task, order	psplib	cumulative, cycle, bin-packing	Java, Prolog	Choco Solver, CHIP, SICStus			generated instance, Roaddef, benchmark, random instance	energetic reasoning, sweep, edge-finding	1110	1640
<a href="#">LiW08</a> <a href="#">386</a>	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	edge-finding	1178	1708
<a href="#">LiseM08</a> <a href="#">388</a>	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
<a href="#">LimtanyakuS12</a> <a href="#">393</a>	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
<a href="#">LombardiM10a</a> <a href="#">402</a>	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	1166	1696

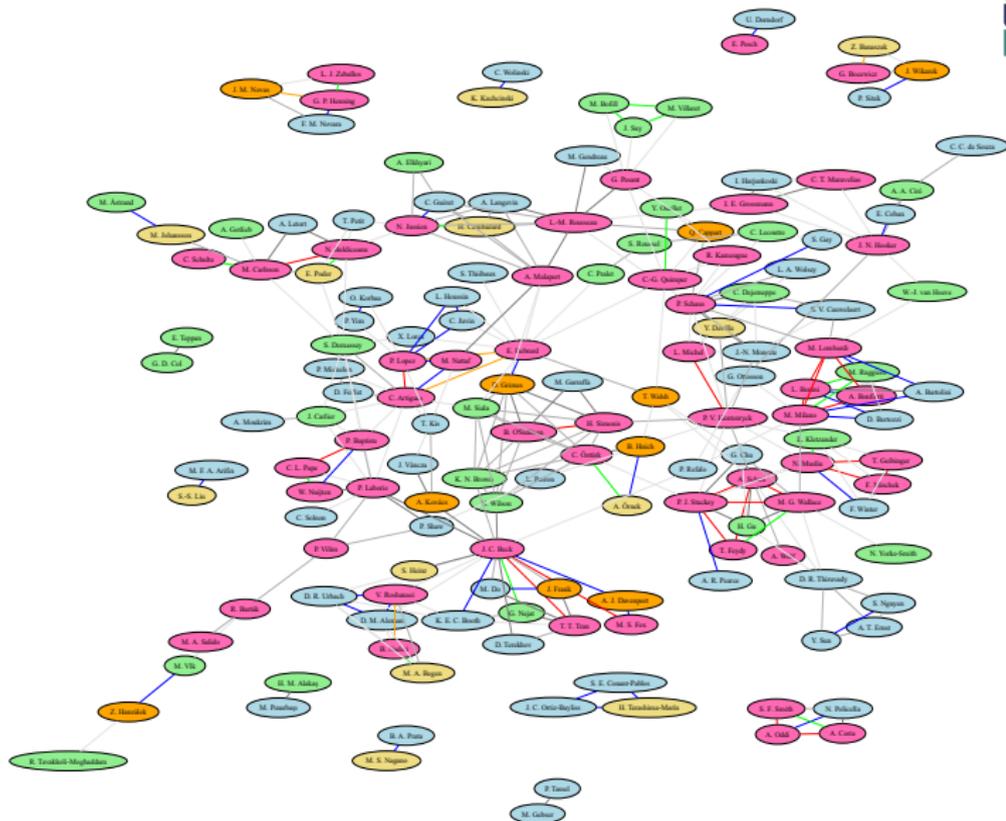
# Extracted Features: Application Areas



Table 16: Works for Concepts of Type ApplicationAreas

Type	Keyword	High	Medium	Low
ApplicationAreas	COVID	<a href="#">GuoZ23</a> <a href="#">269</a>	<a href="#">GebingerKRMW21</a> <a href="#">234</a>	<a href="#">Fatemi-AnarakiTPV23</a> <a href="#">212</a> , <a href="#">Mehdizadeh-Somari23</a> <a href="#">430</a> , <a href="#">GurPAE23</a> <a href="#">220</a> , <a href="#">BavinHL23a</a> <a href="#">331</a> , <a href="#">DujanaAYB23</a> <a href="#">452</a> , <a href="#">Lemo21</a> <a href="#">351</a>
ApplicationAreas	HVAC	<a href="#">LimHTB16</a> <a href="#">390</a> , <a href="#">LimBTB15</a> <a href="#">391</a> , <a href="#">GrimesOS14</a> <a href="#">266</a>		
ApplicationAreas	agriculture			<a href="#">AkramNHBSA23</a> <a href="#">13</a> , <a href="#">BenderWS21</a> <a href="#">84</a> , <a href="#">HamPK21</a> <a href="#">275</a> , <a href="#">Astrand21</a> <a href="#">36</a> , <a href="#">QinWLS21</a> <a href="#">311</a> , <a href="#">Astrand09P21</a> <a href="#">36</a> , <a href="#">MeliaY20</a> <a href="#">431</a>
ApplicationAreas	aircraft	<a href="#">DehIAK22</a> <a href="#">609</a> , <a href="#">WangB20</a> <a href="#">628</a> , <a href="#">TranDRFWOVB16</a> <a href="#">296</a> , <a href="#">Fakhri16</a> <a href="#">205</a> , <a href="#">BajestaniB13</a> <a href="#">42</a> , <a href="#">LombardiM12</a> <a href="#">462</a> , <a href="#">BajestaniB11</a> <a href="#">41</a> , <a href="#">FrankK05</a> <a href="#">219</a> , <a href="#">ArtouchineB05</a> <a href="#">33</a> , <a href="#">Simoni69</a> <a href="#">554</a>	<a href="#">WangB23</a> <a href="#">629</a> , <a href="#">GombokoysWS18</a> <a href="#">253</a> , <a href="#">Ham18</a> <a href="#">274</a> , <a href="#">Simoni07</a> <a href="#">559</a> , <a href="#">SakkouW05</a> <a href="#">529</a> , <a href="#">Simoni69a</a> <a href="#">552</a>	<a href="#">PrataAN23</a> <a href="#">609</a> , <a href="#">PovedaAA23</a> <a href="#">646</a> , <a href="#">Adelgren2023</a> <a href="#">7</a> , <a href="#">ErminanestahatGNMS22</a> <a href="#">262</a> , <a href="#">Eic-OH22</a> <a href="#">104</a> , <a href="#">ZarandiASC20</a> <a href="#">654</a> , <a href="#">HauderBRPA20</a> <a href="#">283</a> , <a href="#">alm-1902-09244</a> <a href="#">262</a> , <a href="#">Hooker19</a> <a href="#">312</a> , <a href="#">LaborieSV18</a> <a href="#">372</a> , <a href="#">HookerH17</a> <a href="#">313</a> , <a href="#">IranAB16</a> <a href="#">324</a> , <a href="#">LombardiM12</a> <a href="#">392</a> , <a href="#">Laborie09</a> <a href="#">370</a> , <a href="#">KovacsB08</a> <a href="#">355</a> , <a href="#">KrogelPLH07</a> <a href="#">608</a> , <a href="#">MartinPY01</a> <a href="#">472</a> , <a href="#">Simoni69</a> <a href="#">556</a> , <a href="#">GruianK98</a> <a href="#">624</a> , <a href="#">Darby-DowdmanMZ07</a> <a href="#">163</a> , <a href="#">Wallace06</a> <a href="#">624</a> , <a href="#">Simoni69</a> <a href="#">557</a> , <a href="#">Simoni09</a> <a href="#">561</a>
ApplicationAreas	automotive		<a href="#">GuoZ23</a> <a href="#">269</a> , <a href="#">YurasockMPV22</a> <a href="#">650</a> , <a href="#">EmdoZD22</a> <a href="#">109</a> , <a href="#">Groleaz21</a> <a href="#">261</a> , <a href="#">LimtanayakniS12</a> <a href="#">303</a> , <a href="#">SomLYL16</a> <a href="#">561</a> , <a href="#">Lombardi10</a> <a href="#">395</a> , <a href="#">BarlatC05</a> <a href="#">32</a> , <a href="#">SchidW09</a> <a href="#">632</a>	<a href="#">PovedaAA23</a> <a href="#">606</a> , <a href="#">NaderiRR23</a> <a href="#">669</a> , <a href="#">CzerniachowskaWZ23</a> <a href="#">159</a> , <a href="#">NaderiBZ22</a> <a href="#">452</a> , <a href="#">NaderiBZ22</a> <a href="#">452</a> , <a href="#">AntuoriHHEN21</a> <a href="#">22</a> , <a href="#">RobnerGSV21</a> <a href="#">618</a> , <a href="#">AkronAPNM21</a> <a href="#">166</a> , <a href="#">KochlerBFHPSSS21</a> <a href="#">314</a> , <a href="#">VIEH21</a> <a href="#">628</a> , <a href="#">BarzegaranZP20</a> <a href="#">61</a> , <a href="#">GebingerMM19</a> <a href="#">236</a> , <a href="#">alm-1911-04766</a> <a href="#">265</a> , <a href="#">BonfattiZLM16</a> <a href="#">113</a> , <a href="#">Sinali5a</a> <a href="#">652</a> , <a href="#">SchneiderH15</a> <a href="#">633</a> , <a href="#">AlessoNBG14</a> <a href="#">181</a> , <a href="#">HarjunkotkiMBC14</a> <a href="#">279</a> , <a href="#">HeiniBGM06</a> <a href="#">63</a> , <a href="#">KovacsV06</a> <a href="#">368</a> , <a href="#">Wallace06</a> <a href="#">628</a>
ApplicationAreas	cable tree	<a href="#">KochlerBFHPSSS21</a> <a href="#">314</a>		
ApplicationAreas	car manufacturing		<a href="#">AntuoriHHEN21</a> <a href="#">22</a>	<a href="#">BeldiceanuC04</a> <a href="#">78</a>
ApplicationAreas	container terminal	<a href="#">QinDCS20</a> <a href="#">512</a> , <a href="#">SacramentoSP20</a> <a href="#">626</a>	<a href="#">LatorreGSV18</a> <a href="#">372</a>	<a href="#">Abe-2312-13058</a> <a href="#">421</a> , <a href="#">PrataAN23</a> <a href="#">608</a> , <a href="#">TomatiB122</a> <a href="#">602</a> , <a href="#">CauwelactD820</a> <a href="#">142</a> , <a href="#">WallaceY20</a> <a href="#">627</a> , <a href="#">ZarandiASC20</a> <a href="#">654</a> , <a href="#">FallahAC20</a> <a href="#">289</a> , <a href="#">Hooker18</a> <a href="#">312</a> , <a href="#">CauwelactDMS16</a> <a href="#">140</a> , <a href="#">DeJemeppe16</a> <a href="#">174</a> , <a href="#">DeJemeppeCS15</a> <a href="#">173</a> , <a href="#">NovasH12</a> <a href="#">416</a> , <a href="#">CurrenL07</a> <a href="#">153</a> , <a href="#">LimTK04</a> <a href="#">339</a>
ApplicationAreas	crew-scheduling	<a href="#">ZarandiASC20</a> <a href="#">654</a> , <a href="#">PourDERB18</a> <a href="#">605</a>	<a href="#">BourreauGGLI22</a> <a href="#">115</a> , <a href="#">Zahouti21</a> <a href="#">652</a> , <a href="#">GrombayWS18</a> <a href="#">253</a> , <a href="#">Mason01</a> <a href="#">429</a> , <a href="#">Touravane03</a> <a href="#">563</a>	<a href="#">NaderiRR23</a> <a href="#">669</a> , <a href="#">WangB23</a> <a href="#">629</a> , <a href="#">Adelgren2023</a> <a href="#">7</a> , <a href="#">ErminanestahatGNMS22</a> <a href="#">262</a> , <a href="#">NaderiBZ22a</a> <a href="#">456</a> , <a href="#">NaderiBZ22</a> <a href="#">452</a> , <a href="#">HeiniNW122</a> <a href="#">605</a> , <a href="#">EicOH22</a> <a href="#">104</a> , <a href="#">Lemo21</a> <a href="#">351</a> , <a href="#">MokhtariataeiPV19</a> <a href="#">29</a> <a href="#">414</a> , <a href="#">TrangLWSK18</a> <a href="#">574</a> , <a href="#">HookerH17</a> <a href="#">313</a> , <a href="#">DowlabiRP16</a> <a href="#">100</a> , <a href="#">LipovetkyBPS14</a> <a href="#">534</a> , <a href="#">HachenGR11</a> <a href="#">272</a> , <a href="#">MilanoW09</a> <a href="#">441</a> , <a href="#">WuBB09</a> <a href="#">623</a> , <a href="#">MilanoW06</a> <a href="#">440</a> , <a href="#">BeldiceanuC02</a> <a href="#">79</a> , <a href="#">JainG01</a> <a href="#">623</a> , <a href="#">Simoni69</a> <a href="#">556</a>
ApplicationAreas	dairies			<a href="#">Bartak02</a> <a href="#">54</a> , <a href="#">Bartak02a</a> <a href="#">53</a>
ApplicationAreas	dairy	<a href="#">EscobetPQFRA19</a> <a href="#">201</a>	<a href="#">PrataAN23</a> <a href="#">609</a> , <a href="#">HarjunkotkiMBC14</a> <a href="#">279</a>	<a href="#">Groleaz21</a> <a href="#">261</a>
ApplicationAreas	datacenter	<a href="#">HermsenRHL11</a> <a href="#">304</a>		<a href="#">Zahouti21</a> <a href="#">652</a> , <a href="#">GalloquilloKSB10</a> <a href="#">225</a> , <a href="#">Mull-WamboldtDM17</a> <a href="#">418</a> , <a href="#">Latorre13</a> <a href="#">382</a> , <a href="#">IrimOS12</a> <a href="#">320</a> , <a href="#">LatorreB12</a> <a href="#">383</a>
ApplicationAreas	datacentre		<a href="#">HurleyOS16</a> <a href="#">310</a>	
ApplicationAreas	day-ahead market			
ApplicationAreas	deep space			<a href="#">HebrardALCMR22</a> <a href="#">285</a>
ApplicationAreas	drone	<a href="#">MontemanniD23a</a> <a href="#">446</a> , <a href="#">MontemanniD23</a> <a href="#">447</a> , <a href="#">Ham18</a> <a href="#">273</a>		<a href="#">GuoZ23</a> <a href="#">269</a> , <a href="#">BavinHL23a</a> <a href="#">331</a> , <a href="#">Adelgren2023</a> <a href="#">7</a> , <a href="#">ShaukhK23</a> <a href="#">647</a> , <a href="#">EmdoZD22</a> <a href="#">109</a> , <a href="#">Astrand21</a> <a href="#">36</a> , <a href="#">Astrand09P21</a> <a href="#">36</a> , <a href="#">AntuoriHHEN21</a> <a href="#">22</a> , <a href="#">ZarandiASC20</a> <a href="#">654</a> , <a href="#">Ham18a</a> <a href="#">274</a>

# Co-Author Graph



# Outline



Siemens Energy Case Study (ASSISTANT)

IHTC 2024

A Generic Scheduling Tool

Literature Survey

Conclusion

# Conclusions



- Constraint Programming is a useful tool for scheduling
- Choice of back-end solver not trivial
  - Feature set
  - Solution quality
  - Deployment options
  - Integration with overall solution
- Use of CP does not require deep understanding of technology
- Visualization key to interpreting results
- Increasing number of "CP inside" papers