The Hybrid Flexible Flowshop with Transportation Times

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What we will discuss

- New variant of known scheduling problem
  - Hybrid Flexible Flowshop with Transportation Times
  - Solved with different approaches
    - CP (4 Versions)
    - MIP (5 Versions)
    - Local Search
  - Spoiler: CP works well, MIP not so much
- Factory layout problem
  - How does the layout affect the scheduling?
  - Compare different high-level design scenarios

A Bit of Background

- Johnson&Johnson is a large multi-national company
  - Strong production and research presence in Ireland
  - Focus on consumer health, medical devices, pharmaceuticals

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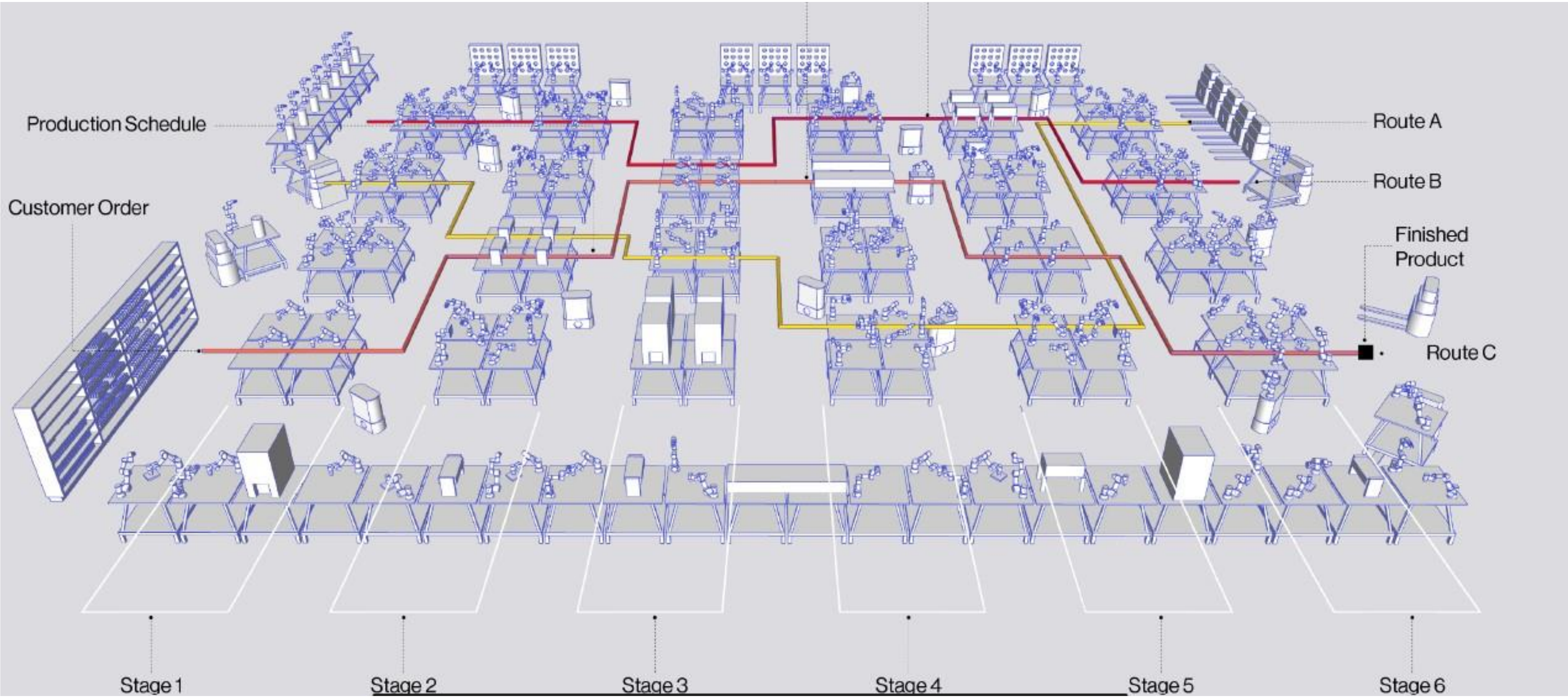
  - Irish National SFI Centre focussed on Manufacturing
  - Includes groups from multiple universities
  - Our focus is on analytics/optimization
  - Complements our work in the Insight SFI Centre for Data Analytics

Problem Description

Flexible Factory Structure (Including Transport Between Machines)



Main Elements of Problem

- Flow shop
  - Jobs run through production in the same sequence
- Hybrid
  - Multiple, identical machines available in each stage
- Flexible
  - Some production stages may be skipped for certain jobs
- Transportation Time
  - Time for transport between stage is significant, but not a resource limit
  - Many robots to handle transport tasks
  - Typical machine layout in lanes
- Objective makespan
  - Production not driven by due-dates

Why is this interesting?

- Industrial Use Case
- Increased complexity over existing hybrid flexible flowshop
- Machines in each stage are no longer exchangeable in schedule
  - Reduced symmetry
  - But also preferred paths through factory

Not Considered in this Study

- Sequence dependent setup times
  - Machines are highly flexible, do not require setup times
- Buffer space
  - Manufactured items are quite small
  - Trays can be stacked in front of machines
- Different production speed on machines of same stage
  - Assumes same generation of machines within each stage
  - (Different stages have different processing times)
- Resource limits on transport
  - No congestion in transport lanes
  - Enough robots to keep material flowing through plant

Objectives of Project

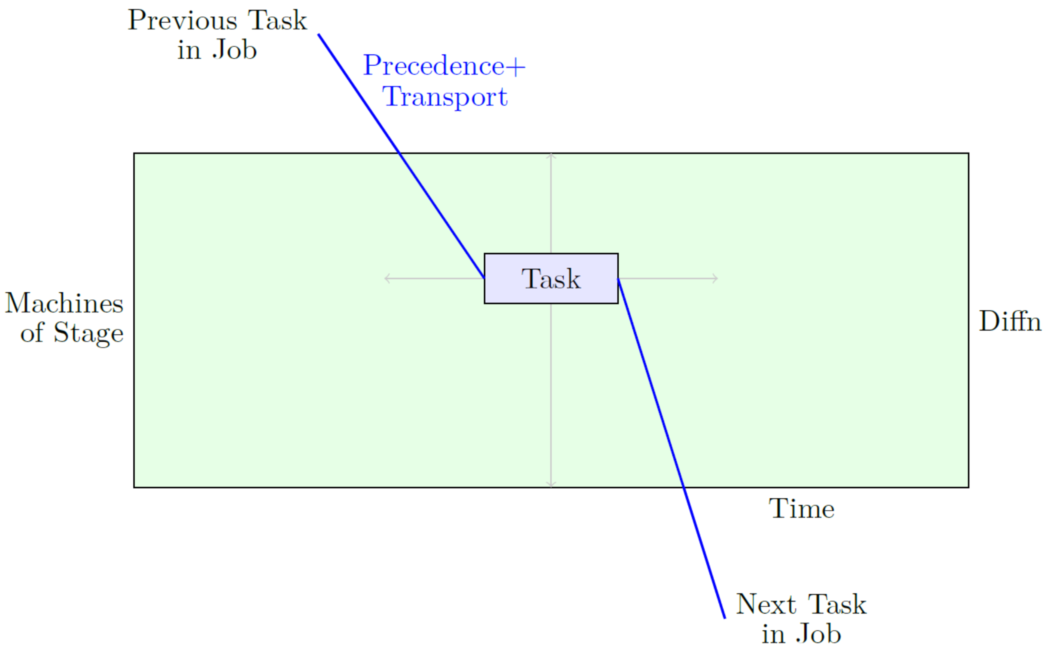
- Identify best tools to schedule new plant
  - Explore variety of different approaches and techniques
  - Do not just focus on your preferred solution method/solver
- Answer some design questions before committing to one approach
  - Is it better to have one or multiple facilities?
  - How far should the transport reach between lanes?
  - How can we exploit flexibility in new machines to offer better products?
    - Semi-custom production
- Provide some quantitative comparison based on typical production data
  - Not currently for operational scheduling

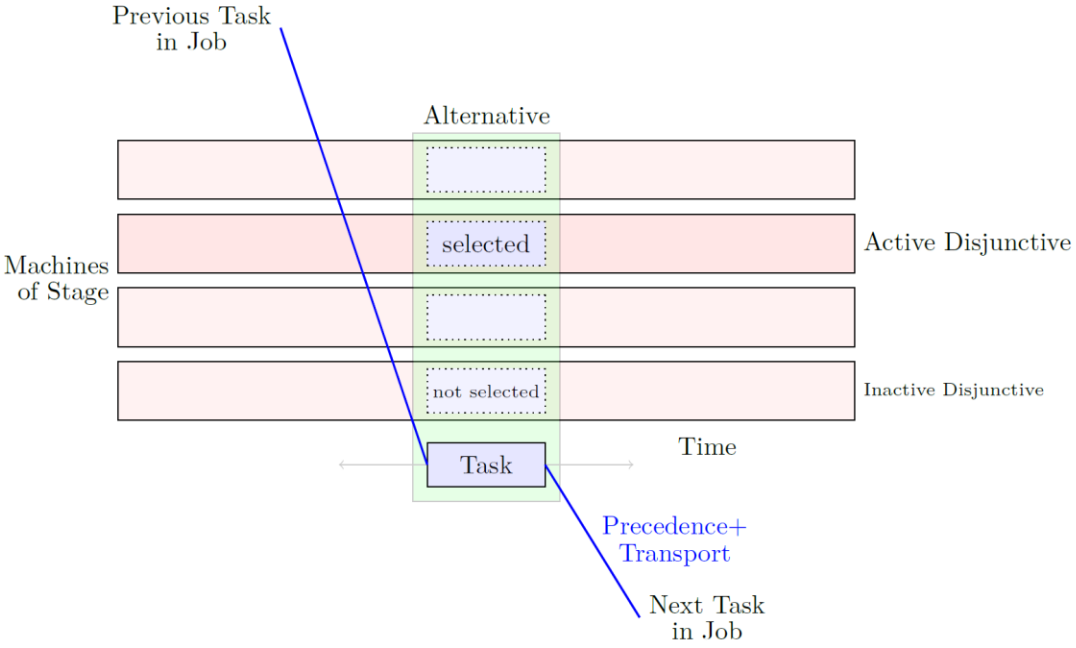
Models

CP Models

- Two main modelling alternatives
  - Diffn model to handle machine choice
  - Interval Task Variables with optional tasks on all alternative machines
- Transportation time handled by table constraint
  - Transportation between machines for tasks of the same job
  - Much simpler case than sequence dependent setup
- Precedences between tasks of jobs
- Objective Cmax (makespan)

CP Model Main Alternative





Dedicated MIP Models

- Four alternatives based on literature for hybrid flexible flowshop
- Adding transportation time grows model complexity
- Picked best alternative on small scale test cases
- None of the methods scale to expected problem sizes

Dispatch Rule/Local Search

- To provide baseline result/ initial upper bound
- Schedule jobs in random order
- Assign each task to first available machine
- Dispatch Rule:
  - Explore different initial job permutations
- Local Search
  - Also explore swaps/insertion of jobs in sequence
- Written in Java

Implementations

- MiniZinc, Chuffed, free search
  - Diffn constraint
- MiniZinc, Chuffed, priority search
- MiniZinc (interval task variables)
- MiniZinc, Cplex
- MIP model, Cplex
- CP Optimizer (interval task variables, black-box search)
- SICStus Prolog (diffn model, custom search)

First Experiment: Compare different solution methods

Instance Generator

- Produce sequence of test cases with increasing number of jobs
  - 20, 25, 30, 40, 50, 100, 200, 300, 400 jobs
  - 25 instances per problem size
- Parameters chosen to reflect real-world factory
  - 8 stages, 10 machines/stage, some skipped stages
  - Discrete power law for job types
    - A few products are quite common, many are rare in order set
  - Transport times based on lanes
- Instances available on-line
  - https://zenodo.org/record/5168966

Experimental Setup

- Experiments run on single core of Windows 10 laptop
- Timeout 300s
- Upper bound provided by 10s of Local Search
- Best lower bound provided to stop search for optimal solutions
  - Optimal solutions found for many smaller (20-30 jobs) instances

Cmax Results with Different Models (average over 25 instances, 300s timeout)

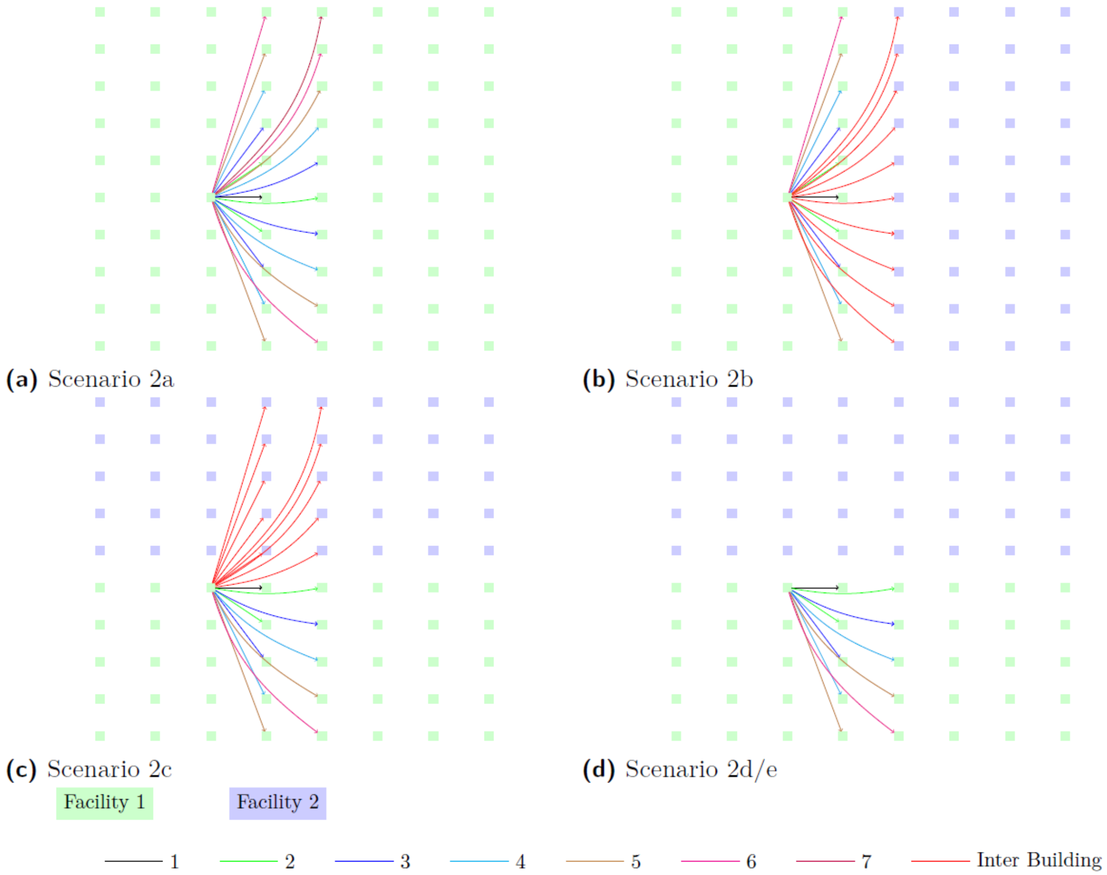
Size	Lower Bound	Upper Bound	CP Opt	Chuffed Free	Chuffed Priority	Dispatch Rule	Local Search	SICStus
20	61.88	63.56	62.72	63.48	63.04	63.28	63.20	62.72
25	62.84	65.96	64.24	-	64.76	65.20	64.84	64.16
30	64.12	70.24	66.68	-	68.44	69.16	68.24	66.84
40	65.32	77.36	72.56	-	75.40	76.08	75.28	73.28
50	67.24	84.52	78.40	-	82.24	83.16	82.24	79.40
100	94.72	120.12	115.16	-	116.96	118.28	118.92	113.04
200	153.08	185.16	180.48	-	181.32	182.80	184.76	176.72
300	214.96	249.12	248.96	-	248.76	246.96	248.88	240.96
400	275.36	311.60	311.28	-	-	308.76	311.40	303.16

Comments

- CP Optimizer and SICStus perform best
  - CP Optimizer better for small/medium instances
  - SICStus does scale better
  - Note: SICStus uses hand-made search routine
  - Chuffed free search does not scale at all
    - Very poor improvements on makespan
  - Chuffed priority search: good initial solutions only
- Dispatch Rule and Local Search perform quite well
  - Further development potential
- MIP does not work at all
  - Limited to smaller instances not shown here

Second Experiment: Study layout alternatives

Four Layout Alternatives (One or Two Locations)



Five Scenarios Tested

- (2a) Single facility organized in lanes
- (2b) Two facilities in sequence (sequential for all jobs)
- (2c) Two facilities in parallel with transport between facilities allowed
- (2d) Two facilities in parallel, transport only within each facility
- (2e) Two factories in parallel, with 80% of jobs preassigned to a factory

Scenario Comparison

		Scenario				
Solver	Size	2a	2b	2c	2d	2e
SICStus	200	176.84	184.84	178.28	180.52	180.48
% over Best		0.00	4.52	0.81	2.08	
CPOptimizer	200	184.40	190.92	186.00	183.52	183.52
% over Best		1.23	4.81	2.11	0.75	
Dispatch	200	182.76	190.44	184.28	184.60	184.64
% over Best		0.00	4.20	0.83	1.01	
Local Search	200	184.68	192.24	185.76	186.08	185.96
% over Best		0.13	4.23	0.72	0.89	

Summary

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- New variant of known scheduling problem
  - Arising from flexible new factory design
  - Transportation between machines/locations important element of schedule
  - Good solutions are obtained with CP for large problem instances
  - Not all CP models achieve the same solution quality
  - MIP results weak
  - Remaining, open gap between best lower bound and best solution found
- Scheduling model used for factory design study
  - Which layout gives the best overall results?
  - Explores four design alternatives

Results Scale to Hundreds of Jobs (shown: SICStus 1000 jobs, 80 machines)

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