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Simultaneous Dynamic Pricing and Scheduling for Manufacturing as a Service

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Main objective:

The goal is to jointly optimize the decisions of production, dynamic pricing, and the placement of orders to suppliers in MAAS systems

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Context & Motivation

- **Partners:** Airbus, TRONICO, Aumovio SE
- **Context:** airplane components and repairs, wide-range electronics, car-related electronics

Opportunities:
- **Internal:** Outsource available capacity to the general-purpose spot market (Airbus, TRONICO)
- **External:** Manage risks and accelerate internal accounting by having a unified platform to submit/receive corresponding orders

Suggestion: Marketplace for Manufacturing as a Service – ACCURATE

- **Place in Industry:** PCB manufacturing, metal sheet manufacturing, 3D-printing
- **Typical Question:** What is the capacity, what is the **price**, and how to **schedule**?

Pricing Component

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Constant Price

Constant price per job type. Same price for the entire time horizon

Static Price

Fixed price per job type, which varies with periods. Price List

- Search with **genetic algorithm**
- Supports an **arbitrary scheduling** approach

Fully Dynamic Pricing

Price depends on **the state and time**. Non-practical due to the huge scheduling state size

Rollout Price

Dynamic price selection requires the estimation of **future state value.** Computationally simplifying heuristic:

- Estimation based on an **arbitrary baseline** policy, e.g. static price
- Supports an **arbitrary scheduling** approach

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Model Based on Willingness To Pay

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Intuition: MaaS serving manufacturing orders

- **Time Periods:** 1, …, T
- **Job Types:** 1, …, N

- **State:** (O_t, A_t) – orders accepted and not yet scheduled, orders accepted and already scheduled
- **Order:** *[n,d]* (*d* pieces of type *n*), with probability q_{nd}
- **Decision:** price per piece $p_{tnd} \in \mathcal{P}_{nd} = \{p_{nd}^1, p_{nd}^2, \dots, p_{nd}^K\}$

- **Willingness To Pay:** $w_{tnd} \sim W_{tnd}(f_t, d_t)$
- **State Transition:** scheduling function S_t + depends if the order is accepted
  - If the price for the order $[n, d]$ is accepted, the next state is computed via: $(O_{t+1}, A_{t+1}) = S_t(O_t + [n, d], A_t)$. Whereas if the price is not accepted, the next state is $(O_{t+1}, A_{t+1}) = S_t(O_t, A_t)$

- $J_t(O_t, A_t)$ - **value to go**, $V_t(O_t, A_t)$ – **cost of job execution and delivery** for jobs from (O_t, A_t) to (O_{t+1}, A_{t+1}), where $(O_{t+1}, A_{t+1}) = S_t(O_t, A_t)$
- **Dynamic Program:**

$$J_t(O_t, A_t) = \sum_{n=1}^{N} \sum_{d=1}^{D} q_{nd} \max_{p_{tnd} \in \mathcal{P}_{tnd}} \mathop{\mathbb{E}}_{w_{tnd} \sim W_{tnd}} \Big\{ \mathbb{P}(w_{tnd} > p_{tnd})(dp_{tnd} - V_t(O_t + [n, d], A_t)$$

$$+ J_{t+1}(S_t(O_t + [n, d], A_t)) + \mathbb{P}(w_{tnd} < p_{tnd})(J_{t+1}(S_t(O_t, A_t)) - V_t(O_t, A_t)) \Big\}$$

Company RM: Static Price

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Static Policy – Pricing with a static price table and scheduling with a pre-specified algorithm (currently – FIFO)

	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8
Job 1	5$	10$	5$	5$	10$	15$	15$	15$
Job 2	20$	20$	30$	30$	40$	20$	20$	20$

Genetic Search For a Static Policy

Algorithm Genetic Search

function GeneticSearch($\mathcal{P}_0, N_g, N_t, N_s, N_f$):
▷ $\mathcal{P}_0$ - initial population of static pricing policies
▷ N_g - number of genetic iterations
▷ N_t - number of trajectories for stochastic estimation in progress
▷ N_s - number of policies that survive selection between epochs
▷ N_f - number of trajectories for final policy selection

$\mathcal{T}_0 \leftarrow$ SampleTrajectories(N_t) ▷ $\mathcal{T}_k$ is the set of trajectories for evaluation at k-th epoch
$\mathcal{L}_0 \leftarrow \{$SelectOptimal($\mathcal{P}_0, \mathcal{T}_0$)$\}$ ▷ $\mathcal{L}_k$ is the set of optimal static policies at first k epochs
for $i \in [1, ..., N_g]$ **do**:
  $\mathcal{T}_i \leftarrow$ SampleTrajectories(N_t)
  $\mathcal{G}_i \leftarrow$ FormNextGeneration($\mathcal{P}_{i-1}$)
    ▷ $\mathcal{G}_i$ is the set of static policies obtained during genetic expansion
  $\mathcal{P}_i \leftarrow$ SelectNBest($\mathcal{G}_i$, $\mathcal{T}_i$, N_s)
    ▷ $\mathcal{P}_i$ is the set of static policies that have surpassed genetic selection
  $\mathcal{L}_i \leftarrow \mathcal{L}_{i-1} \cup$ SelectOptimal($\mathcal{P}_i$, $\mathcal{T}_i$)
end for
$\mathcal{T}_f \leftarrow$ SampleTrajectories(N_f) ▷ $\mathcal{T}_f$ - Trajectories for final static policy selection
return SelectOptimal($\mathcal{L}_{N_g}$, $\mathcal{T}_f$)
end function

Parameter	Value
# Genetic Iterations	100
# Evaluation Trajectories	50
# Mutation Places	10
Recombination Probability	0.5
# Selection	10

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Company RM: Rollout Algorithm

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Idea: Value function approximation

1. Stochastic state value estimation with existing policy (e.g., Static Price Policy)
2. The next decision is locally optimal according to all prices tried now and further applying the existing policy

Arbitrary scheduler supported. FIFO in reported experiments

Rollout Policy:

$$\tilde{R}_t^{\pi}(O_t, A_t) = \sum_{n=1}^{N} \sum_{d=1}^{D} q_{nd} \max_{p_{tnd} \in \mathcal{P}_{tnd}} \mathop{\mathbb{E}}_{w_{tnd} \sim W_{tnd}} \Big\{ \mathbb{P}(w_{tnd} > p_{tnd})(dp_{tnd} - V_t(O_t + [n,d], A_t) + \tilde{J}_{t+1}^{\pi}(S_t(O_t + [n,d], A_t)) + \mathbb{P}(w_{tnd} < p_{tnd})(\tilde{J}_{t+1}^{\pi}(S_t(O_t, A_t)) - V_t(O_t, A_t)) \Big\}$$

k-Nested Policy:

$$\tilde{R}_t^{\pi,k+1}(O_t, A_t) = \sum_{n=1}^{N} \sum_{d=1}^{D} q_{nd} \max_{p_{tnd} \in \mathcal{P}_{tnd}} \mathop{\mathbb{E}}_{w_{tnd} \sim W_{tnd}} \Big\{ \mathbb{P}(w_{tnd} > p_{tnd})(dp_{tnd} - V_t(O_t + [n,d], A_t) + \tilde{R}_{t+1}^{\pi,k}(S_t(O_t + [n,d], A_t)) + \mathbb{P}(w_{tnd} < p_{tnd})(\tilde{R}_{t+1}^{\pi,k}(S_t(O_t, A_t)) - V_t(O_t, A_t)) \Big\}$$

Company RM: Perfect Information

Observation: With perfect information, the decision is acceptance-rejection

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Features:

- Groups with the same types of jobs: $G_1, G_2, \dots, G_T$ correspond to orders
- G_g - set of all jobs in group g
- $G = G_1 \cup \dots \cup G_T$ - the set of all job indices
- If the group is accepted, all job within the group is either processed or declined
- Jobs numbered independently: $G_1 = \{1, \dots, |G_1|\}, G_2 = \{|G_1| + 1, \dots, |G_1| + |G_2|\}, \dots$
- Set of all machines: M, M_j - machines compatible with job j

Input parameters:

- v_g - **per-job valuation** in group G_g
- π_{ij} - **processing time** of job j on machine i
- τ_{ij} - post-processing job **delivery time** for job j from machine i
- ρ_j - **decline cost** per job j
- d_j - **due date** of job j
- r_j - **release time** of job j
- w_j- **delay penalty** of job j
- g_j- the **index** of the group of job j
- H – **upper bound** on job completion time

Decisions:

- a_g - **acceptance** decision for group with index g
- $0 \le s_j \le H$ – job processing **start** time
- y_{ij} - job-machine **assignment** variable, $i \in M_j$
- $\delta_j \in \{0, 1\}$ - job **decline** decision

Variables:

- $0 \le c_j \le H$ – job **completion** time
- $0 \le \Delta_j \le H$ – **tardiness**
- $z_{jk} \in \{0, 1\}$ - job **precedence** variables

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Company RM: Perfect Information

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Perfect-Information Objective:

$$\sum_{g=1}^{T} a_g |G_g| v_g - \sum_{j=1}^{|G|} \delta_j \rho_j - \sum_{j=1}^{|G|} w_j \Delta_j$$

Constraints:

1. **Allocation statement**, ensuring that if the group is accepted, each job within the group is either processed or declined: $\sum_{i \in \mathcal{M}_j} y_{ij} + \delta_j = a_{g_j}, \forall j \in G$. If the group is rejected, both processing and declining variables are set to zero

2. Inequalities $z_{jk} \leq a_g, \forall j \in G, \forall k \in G, j \neq k, \forall g \in \{g_j, g_k\}$, and $z_{jk} \leq \max\{1 - \delta_j, 1 - \delta_k\}$, $\forall j \in G$, $\forall k \in G$, $j \neq k$, that essentially request **precedence indicator set to zero when one of the jobs is declined or is from a rejected group**

3. Inequalities $c_j \geq s_j + y_{ij}(\pi_{ij} + \tau_{ij}), \forall j \in G, \forall i \in \mathcal{M}_j$ requesting that **completion** time of job j **happens after processing starts, job executed and delivered**

4. Statements $\Delta_j \geq c_j - d_j, \forall j \in G$, ensuring **correct computation of tardiness**, together with the requirement $0 \leq \Delta_j \leq H$ mentioned above

5. Inequalities $s_j \geq a_{g_j} r_j, \forall j \in G$, requiring that **job processing starts after the job release** time

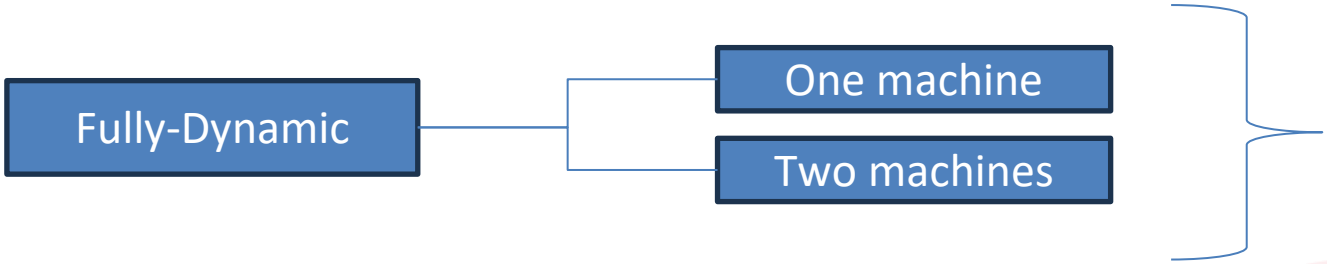
6. **Precedence constraints**, ensuring that if scheduled at the same machine, job execution intervals do not intersect: $\forall i \in \mathcal{M}_j \cap \mathcal{M}_k, \forall k \in G, \forall j \in G, k \neq j$:

$$s_k \geq (s_j + \pi_{ij}) - H(3 - y_{ij} - y_{ik} - z_{jk})$$
$$s_j \geq (s_k + \pi_{ik}) - H(2 - y_{ij} - y_{ik} + z_{jk})$$

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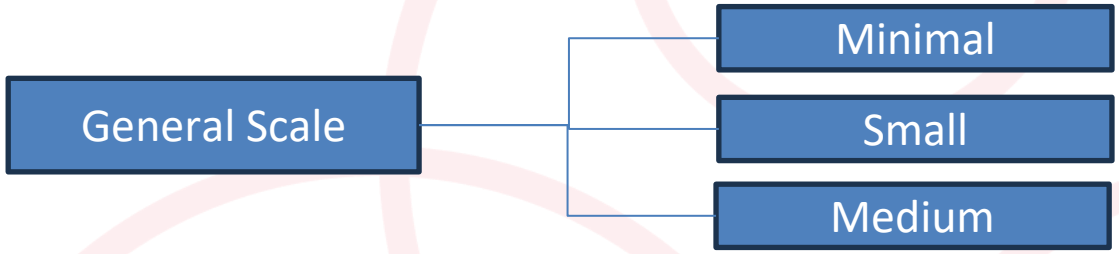
Experiment Plan

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Fully-dynamic settings:

- One job per order, two job types, two price tiers
- Optimal expected revenue, dynamics on profile (mask-based search), limited number of time periods ($T \leq 20$)
- Evaluated dynamic, static (all possible, $T \leq 6$), and constant pricing policies



For **general** settings:

- Instances generated **randomly**
- **Genetic**-based algorithms
- **Gurobi** solver for perfect information upper bound
- Price policies: **static, rollout, k-nested**

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Company RM: Experiment Configurations

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Settings: Minimal, Small, Medium

Parameter	Minimal	Small	Medium
Period Duration	U([12,24])	U([12,24])	U([12,24])
Number of Machines	1	1	2
Number of Job Types	1 (small)	2 (small, large)	2 (small, large)
Number of Periods	10	20	20
Job Type Probabilities	1	{0.8, 0.2}	{0.8, 0.2}

Minimal Setting: 1 machine, 1 job type

Small Setting: 1 machine, 2 job types

Medium Setting: 2 machines, 2 job types

Job Type	Easy	Hard
Linear Sensitivity	1 / 25	1 / 75
Count In Order	10 in minimal 50 in small, medium	30
Duration Before Available	12 in minimal 18 in small, medium	12
Duration To Due Period	24 in minimal, 48 in small, medium	72
Delay Cost	0.25	0.75
Decline Cost	50 in minimal 100 in small, medium	300
Compatible Machines	{0} in minimal, small {0, 1} in medium	{0,1}
Duration Per Machine	{0.25} in minimal, small {0.25, 0.5} in medium	{1.5} in small, {1.5, 3.2} in medium
Delivery Per Machine	{3} in minimal, {1} in small, {1, 1} in medium	{1} in small, {1, 1} in medium
Possible Prices	{5, 15, 25} [U {10, 20} in minimal]	{25, 50, 75}

Company RM: Experiment Results

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Instance	Genetic Static	Genetic Rollout	Genetic Nested
Minimal	94.89	416.59	453.92
Small	891.05	3132.72	3206.05
Medium	2040.8	5585.21	N/E

Genetic Optimization Summary:
- Static < Rollout < Nested
- Nested is slow in scale
- Rollout is **2.7** times more profitable than static on Medium, **3.5** times more profitable on Small, **4.4** times more profitable on Minimal

Perfect Information Results:

Instance	Gurobi Integral	Gurobi Continuous
Minimal	1007.26	1015
Small	1555.49	9800
Medium	685.86	9800

Gurobi Integral – Heuristics
Gurobi Continuous – Upper Bound (Continuous Values)

Gurobi MIP Limits: 100 sec, 300 sec, 400 sec

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Thank you for your attention!

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Summary:

1. **Genetic Search** for an Optimal Static Price Policy
2. Dynamic **Rollout** for a Static Policy
3. **K-Nested** Rollout for a Static Policy
4. Extension for **Multiple** Manufacturing Service **Providers** (appendix)

Contribution:

1. Dynamic Stochastic Model of **Joint** Dynamic Pricing and Scheduling Decision based on **Willingness to Pay**
2. **Multi-provider Utility-Based** Extension with **Dynamic Equilibrium** in Price Decisions (appendix)
3. **State-based stochastic pricing** model with support for an **independent combinatorial scheduling** component
4. Numeric Evaluation

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Appendix A. Extension: Decision-Free Manufacturing Service Platform (multi-provider case, work in progress)

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Several Manufacturing Service Providers, Utility-Based Decision, Multinomial Choice Model, Dynamic Equilibrium in Prices

Exact Evaluation - Experiment Configuration

1. **Time Horizon:** from 1 to 8
2. **Two Types Of Jobs:** Easy and Complex
3. **Easy Job:** Tardiness Fee = 2, Decline Fee = 60, Release Term = 0, Due Term = 5, Proper Valuation = 56, Attractiveness Sensitivity = 1, Price Sensitivity = 1, Probability = 0.8
4. **Complex Job:** Tardiness Fee = 4, Decline Fee = 175, Release Term = 1, Due Term = 8, Proper Valuation = 120, Attractiveness Sensitivity = 2, Price Sensivity = 1, Probability = 0.2
5. **Two Types of Providers:** Typical and Premium
6. **Two Manufacturing Service Providers**
7. **Typical Provider:** 1 machine supporting both jobs, 3 price tiers per job, Easy Prices: [11, 22, inf], Complex Prices: [26, 36, inf], Easy Duration = 2, Complex Duration = 3, Easy Delivery = 1, Complex Delivery = 2
8. **Premium Provider:** 1 machine supporting both jobs, Easy Prices: [20, 30, inf], Complex Prices: [31, 51, inf], Easy Duration = 1, Complex Duration = 2, Easy Delivery = 1, Complex Delivery = 1

Horizon	1	2	3	4	5	6	7	8
Typical	0.0	8.77	10.52	19.28	21.31	30.07	32.19	40.91
Premium	24.0	24.0	29.40	34.52	39.76	45.73	51.58	57.70
Time (sec)	**0.05**	**0.07**	**0.31**	**1.86**	**8.87**	**28.09**	**152.03**	**829.29**

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Premium earns **at least 25% more**

Appendix B. FAQ

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State of The Art:

1. Heuristic pricing according to time series, corrected with some statistics from production state
2. Queue-based scheduling model and pricing on top. Relevant for hospitals, less realistic for production
3. Game-theoretic manufacturing configurations considering price-only decisions
4. Genetic approaches for scheduling-related problems in 3D printing, metal sheet manufacturing, and PCB contexts
5. Pricing through auctions
6. Joint pricing and transportation (or other complex) decisions

Appendix B. FAQ

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Positions of Contribution:

1. State-based dynamic price formulation and approach
2. Competitive configuration with multiple providers (utility-based choice)
3. Revenue management for a single MaaS company (decision based on willingness-to-pay)

Scalability and Practical Relevance:

1. Can process one-two months of industrial-scale data
2. Quality needs more samples and higher computation time
3. Industrial scale – a year (six times longer)

Appendix C. Selected Literature

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16. MASTT 2040 **White Paper by Sirris**

Appendix D. Company RM: Fully Dynamic Pricing

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Parameter	Value
Time Horizon	≤ 20
Job Types	Complex, Easy
Job Type Probabilities	Complex: [0.3 | 0.2 | 0.1] Easy: [0.7 | 0.8 | 0.9]
Job Durations	1, 2
Price Tiers / Willingness To Pay	Expensive, Cheap
Tier Probabilities	Cheap: [0.7 | 0.8 | 0.9] Expensive: [0.3 | 0.2 | 0.1]
Decline Cost	400$ / 100$
Delay Penalty	40$ / 10$
Number of Machines	1

Profit At Durations By Tier:

	Expensive	Cheap
Easy	80$	10$
Complex	260$	100$

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Appendix D. Company RM: Fully-Dynamic Experiment Results

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Horizon	1	2	3	4	5	6	7	8	9	10
Dynamic	0.0	8.0	36.96	79.01	101.83	139.24	167.55	198.06	242.38	267.09
Constant	0.0	3.6	12.2	48.06	59.29	82.85	95.82	108.44	152.26	163.63
Static	0.0	8.0	36.4	69.55	97.58	123.45	N/A	N/A	N/A	N/A
Horizon	11	12	13	14	15	16	17	18	19	20
Dynamic	305.34	334.41	365.43	409.91	434.9	473.24	502.42	533.51	578.01	603.03
Constant	187.23	200.21	212.84	256.66	268.02	310.83	306.99	368.53	407.76	414.39

Expected revenues, stylized setting with **one machine**

Difference for a setting with two machines:

1. **Easy** Job: Due in 6 days, the 1st machine completes in 1 day, the 2nd in 2 days. Delivery time is 1 day for the 1st machine, 2 days for the 2nd machine
2. **Complex** Job: Due in 7 days, 1st machine completes in 2 days, 2nd in 3 days. Delivery times are 1 day for the 1st machine, 2 days for the 2nd machine

Horizon	1	2	3	4	5	6	7	8	9	10	11	12
Dynamic	0.00	8.00	36.96	84.32	107.10	146.59	176.82	207.44	254.59	277.56	317.18	347.41
Static	0.00	8.00	36.40	82.70	105.70	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Constant	0.00	3.60	12.20	48.58	60.19	83.52	96.48	108.92	152.98	164.59	188.09	200.88

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Expected revenues, stylized setting with **two machines**