POLITECNICO MILANO 1863

DIPARTIMENTO DI MECCANICA

Dynamic Programming for Energy State Control of Machine Tools in Manufacturing with Part Admission Control

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Outline

- Introduction and State of the Art
- Assumptions
- DP Model
- Numerical Results
- Conclusions and Future Developments

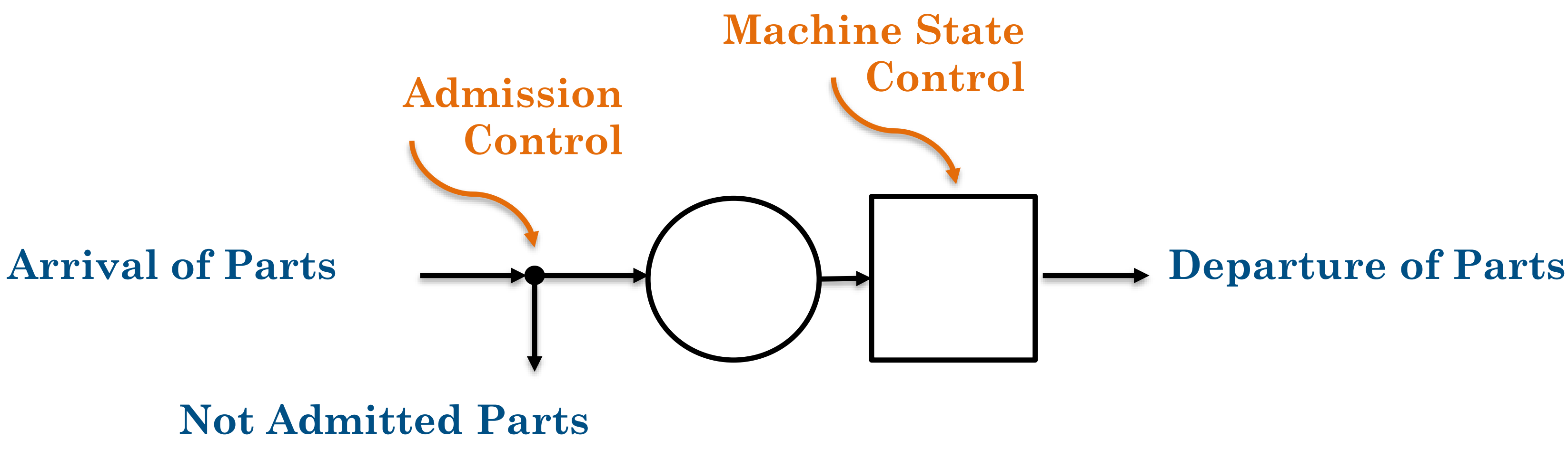
Introduction and State of the Art

This work focuses on the combined problem of:

- Controlling the switching off/on of machine tool for energy saving purposes;
- Controlling the admission of parts;

using buffer occupancy information from the upstream buffer.

The problem is to dynamically control the system so as to minimize discounted cost.



Introduction and State of the Art

- The **control of admission** aims at **reducing the congestion** (in the form of jobs waiting in the buffer) in a system.
- A cost incurs whenever a customer is rejected (or, equivalently, a reward is earned whenever a customer is accepted).
- Problems of this type have been studied in the literature (e.g. [1] [2] [3][4]) and it is shown that threshold policies are optimal.
- Also finite capacity systems can be modeled by increasing the holding cost when the queue length reaches the capacity.

[1] Serfozo, R.: Optimal control of random walks, birth and death processes, and queues. Adv. Appl. Probab. 13, 61–83 (1981)
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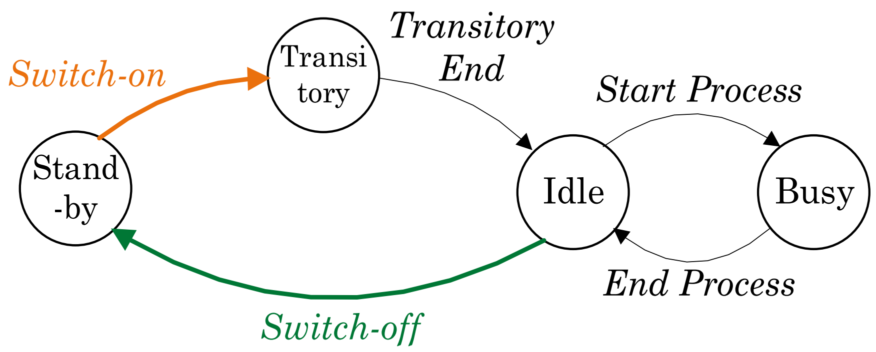
Introduction and State of the Art

- The **control of machine states** for energy saving aims at **reducing the amount of energy required when the machine is not working on parts (idle).**
- The service is interrupted and resumed based on **time** information or on the **buffer level** information.
- Vacation queueing theory, Dynamic Programming, Simulation, …



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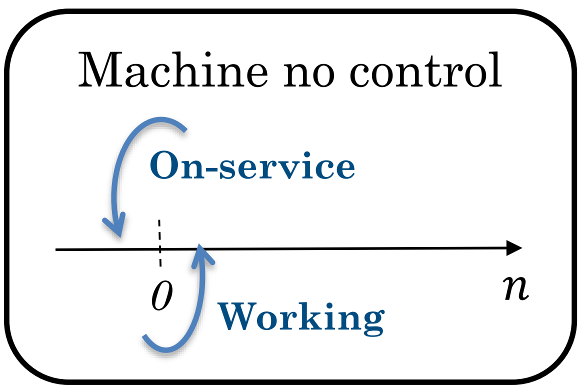
[10] Frigerio N. 2016. Optimal Stochastic Switching of Machine Tools in Energy Efficient Manufacturing Systems, PhD Thesis, Politecnico di Milano, Italy.

The objective is to minimizing total discounted cost with:

- Machine energy cost $c(x)$ with x = machine state;
- Inventory holding cost $h(n)$ where $h(\cdot)$ is convex on number of parts n;
- Production reward $r \geq r_{\min}$ earned at process completion.

The **optimal policy** is an **exhaustive service discipline**:



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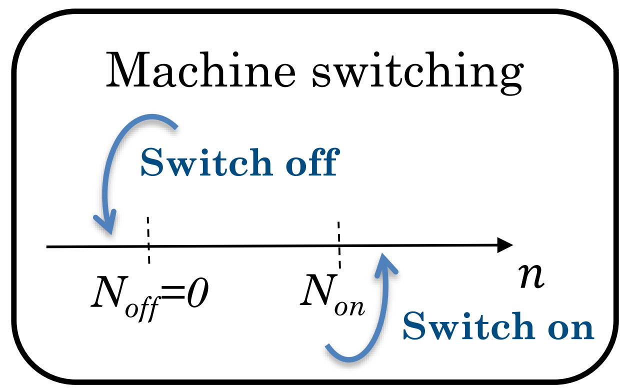

[10] Frigerio N. 2016. Optimal Stochastic Switching of Machine Tools in Energy Efficient Manufacturing Systems, PhD Thesis, Politecnico di Milano, Italy.

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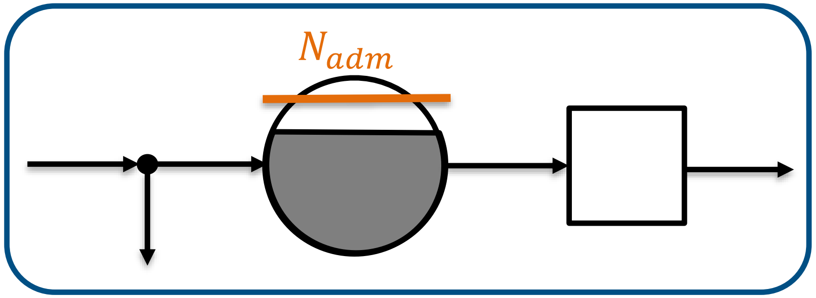
Contribution

1) The development of a dynamic programming based model for the combined optimization problem of controlling machine state and part admission;
2) To analyze structural properties of the control such as (with $r > r_{\min}$):
   - Exhaustive service;
   - Parts are admitted up to threshold N_{adm};
   - The machine is switched off when buffer is empty ($N_{off} = 0$), and it is switched on after N_{up} parts accumulates into the system.



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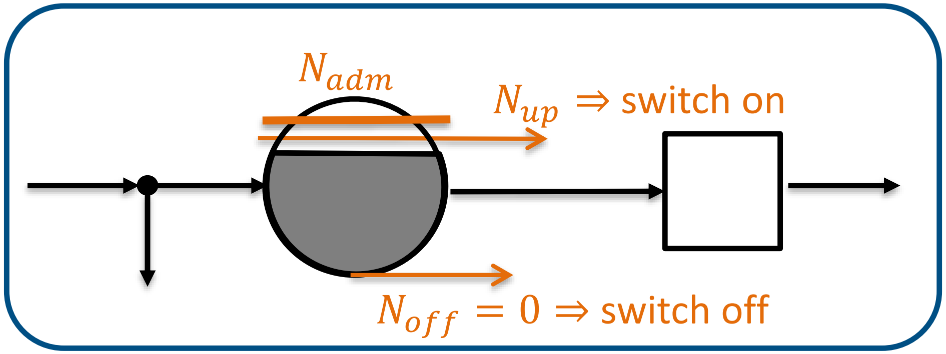
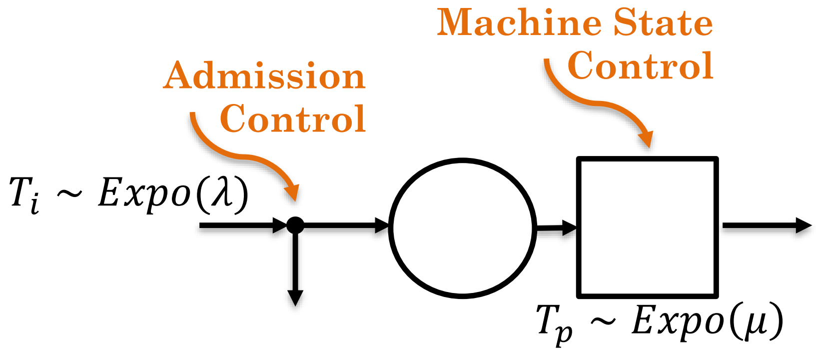


Assumptions



1. Perfectly reliable server;
2. Infinite downstream buffer;
3. Transitory (startup) durations are i.i.d. random variables $T_{\mathrm{su}} \sim Expo(\gamma)$;
4. The startup is long enough to guarantee the quality of processed parts;
5. The random variables are not affected by the control;
6. The stochastic process are independent each other;
7. **Machine processing and startup cannot be interrupted by the control.**

Dynamic Programming Approach

The control problem can be modeled as **Discrete Time Markov Decision Process** problem with the **uniformization** technique (Lippman [15]):

- A countable number of states;
- Random time between transitions;
- Observable system state;
- The feasible control action set depends on system state and event occurrence.

[11] S.A. Lippman. Applying a new device in the optimization of exponential queueing system. Operation Research, 23:687–710, 1975
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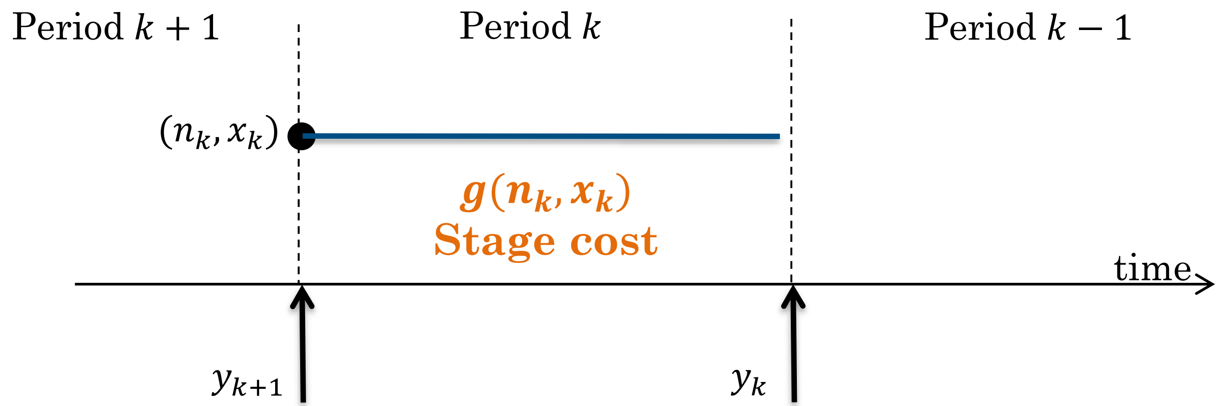
Model (part I)



Denote a period k when k transitions are left.

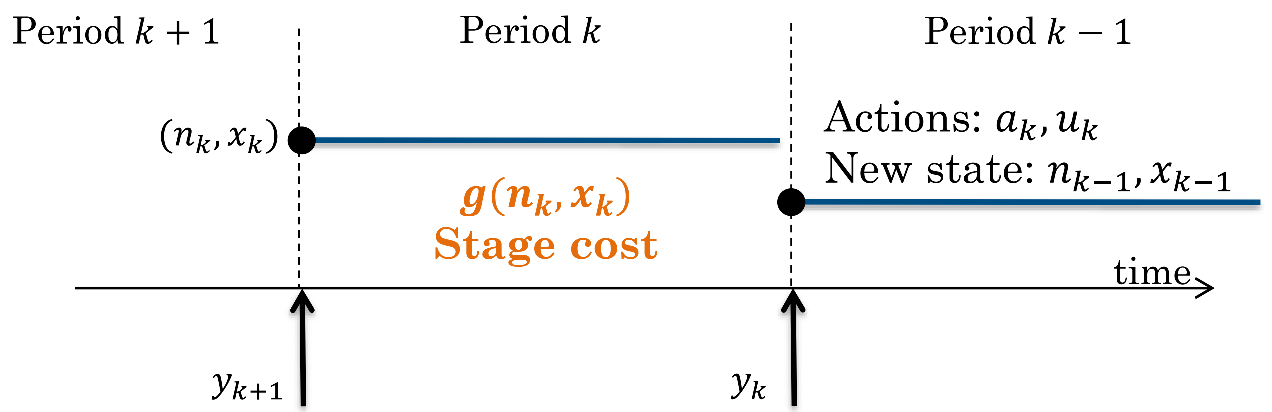
Decision Epochs are the occurrences of event $\boldsymbol{y_k}$ at the end of period k:

$$y_k = \begin{cases} \text{A} - \text{part } \textbf{A}\text{rrival} \\ \text{D} - \text{part } \textbf{D}\text{eparture} \\ \text{C} - \text{startup } \textbf{C}\text{ompletion} \end{cases}$$

System State $(\boldsymbol{n_k}, \boldsymbol{x_k})$ observed at the beginning of period k:

- $\boldsymbol{n_k}$ = number of parts in the system;
- $\boldsymbol{x_k}$ = machine state $x \in \{1,2,3,4\}$.

Model (part II)



Control Actions $(a_k, u_k) \in A(n_k, x_k, y_k)$ that is the set of feasible actions depending on system state (n_k, x_k) and event instance y_k.
Actions are taken at the end of period k after the event is observed.

- Upon arrival, a part is admitted if $u_k = 1$, otherwise $u_k = 0$
- The machine state is controlled according to machine model with a_k

  e.g. if $x_k = 1 \Rightarrow a_k \in \{1,3\}$

System Dynamics is assumed to be stationary.

Model (part III)

System Dynamics

System dynamics is assumed to be stationary.

Given the current system state (n_k, x_k) the instance of event y_k, and the control actions (a_k, u_k), the next system state (n_{k+1}, x_{k+1}) is as follows:

$$(n_{k+1}, x_{k+1}) = \mathbb{Z}(n_k, x_k, y_k, a_k, u_k)$$

$$(n_{k+1}, x_{k+1}) = \begin{cases} (n_k + u_k, a_k) & \text{if } y_k = \text{A} \\ (n_k - 1, a_k) & \text{if } y_k = \text{D} \\ (n_k, a_k) & \text{otherwise} \end{cases}$$

Where action a_k is in a feasible ation set (Table 1).

Table 1 : Feasible action set

x	n	y	$\mathscr{A}_{s,y}$
1	$\forall n$	A$\vee\emptyset$	{1,3}
2	$n > 0$	A$\vee\emptyset$	{1,2,4}
	$n = 0$	A	{1,2,4}
		$\emptyset$	{1,2}
3	$n > 0$	A$\vee\emptyset$	{3}
		C	{1,2,4}
	$n = 0$	A$\vee\emptyset$	{3}
		C	{1,2}
4	$n > 1$	A$\vee\emptyset$	{4}
		D	{1,2,4}
	$n = 1$	A$\vee\emptyset$	{4}
		D	{1,2}

Model (part IV)

The **infinite-horizon optimal discounted cost** is: $J = \sum_{k=1}^{\infty} \min_{a_k, u_k} \mathbf{E}[f(n_k x_k, a_k, u_k)]$

- Machine energy cost $c(x)$ where c(4) > c(2) > c(1) and c(3) > c(2);
- Inventory holding cost $h(n)$ where the convexity holds:

$$h(n+2) - h(n+1) \geq h(n+1) - h(n)$$

- Rejection cost $c_r(n) \geq 0$ when the part is rejected;
- Production reward $r \geq 0$ earned at process completion.
  - It represents the valuable reward for the production of each part;
  - It may be correlated to the downstream-system (as r increases, the control is prone to be more productive).

Model (part V)

Given a discount rate α, $v^*_{k+1}(n_{k+1}, x_{k+1})$ denotes the discounted cost when *k+1* transitions are left:

$$v^*_{k+1}(n_{k+1}, x_{k+1}) = g(n_{k+1}, x_{k+1}) + \mathrm{E}_{(a_{k+1},u_{k+1})}[v^*_k(n_k, x_k | n_{k+1}, x_{k+1})]$$

$$\lim_{k\to\infty} v^*_k(n,x) = v^*(n,x) = J$$

For example:

$$v^*_{k+1}(n,4)\Big|_{n>1} = \frac{h(n)+c(4)}{\eta}$$

Stage Cost

Arrival → $+\dfrac{\lambda}{\eta}\min_{u=\{0,1\}} v^*_k(n+u,4)$

Departure → $+\dfrac{\mu}{\eta}\left[-r + \min_{a=\{1,2,4\}} v^*_k(n-1,a)\right]$

Uniformization term → $+\dfrac{\eta-\lambda-\mu-\alpha}{\eta} v^*_k(n,4)$

Cost – To – Go

Note: $\eta = \lambda + \mu + \gamma + \alpha$

Experimental Setting

- Numerical data are obtained with value iteration algorithm in Matlab©:
  - 20'000 iterations (difference between iterations smaller than 0.1%)
  - Finite number of states: $n = 0, 1, \dots 200$

The optimality of **threshold based** policies is shown.

The advantage of combined control is shown by comparing four policies:
P1 – No control (admit all, machine no controlled)
P2 – Machine state control (admit all)
P3 – Admission control (machine no controlled)
P4 – Machine state control and admission control

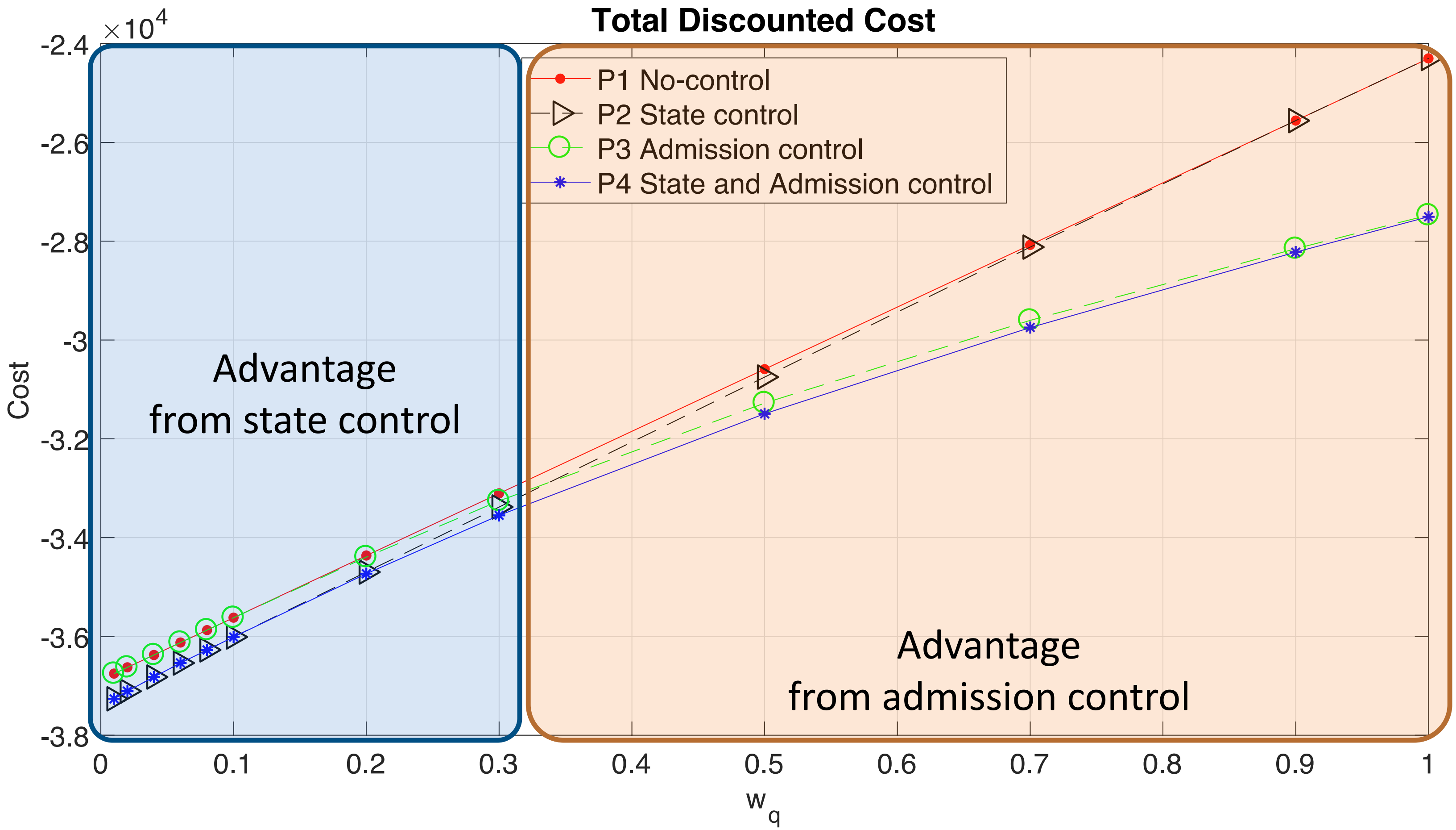
- Special case: $r < r_{min} \Rightarrow$ no production advantage (no admission / no production)

- Sensitivity analysis is performed. Detailed results for:
  - Holding cost $h(n) = w_q n$
  - Arrival rate λ

Holding cost $h(n) = w_q n$

$c_{out} = 0$
$c_{on} = 1$
$c_{su} = 1.91$
$c_{work} = 5.18$
$t_p = 1$

$t_a = 1.25$
$t_{su} = 0.23$
$r = 20$
$c_r = 0$
$\alpha = 10^{-5}$



Holding cost $h(n) = w_q n$

$c_{out} = 0$
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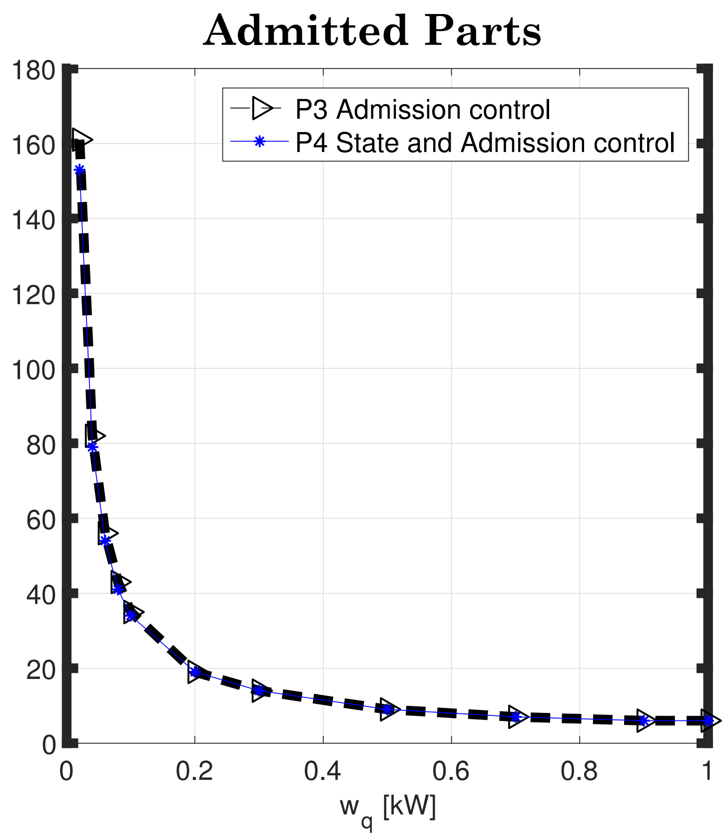
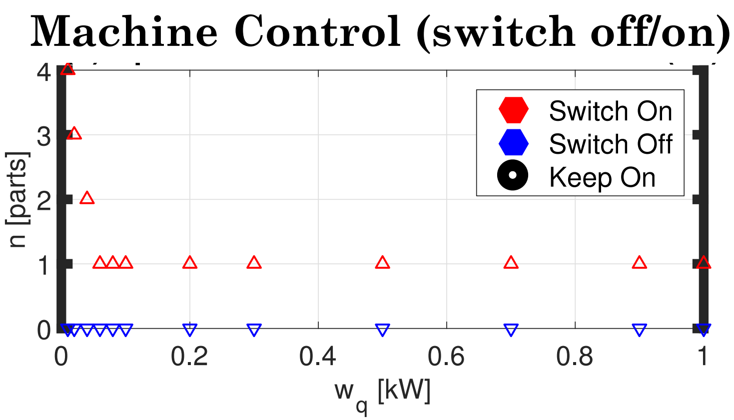
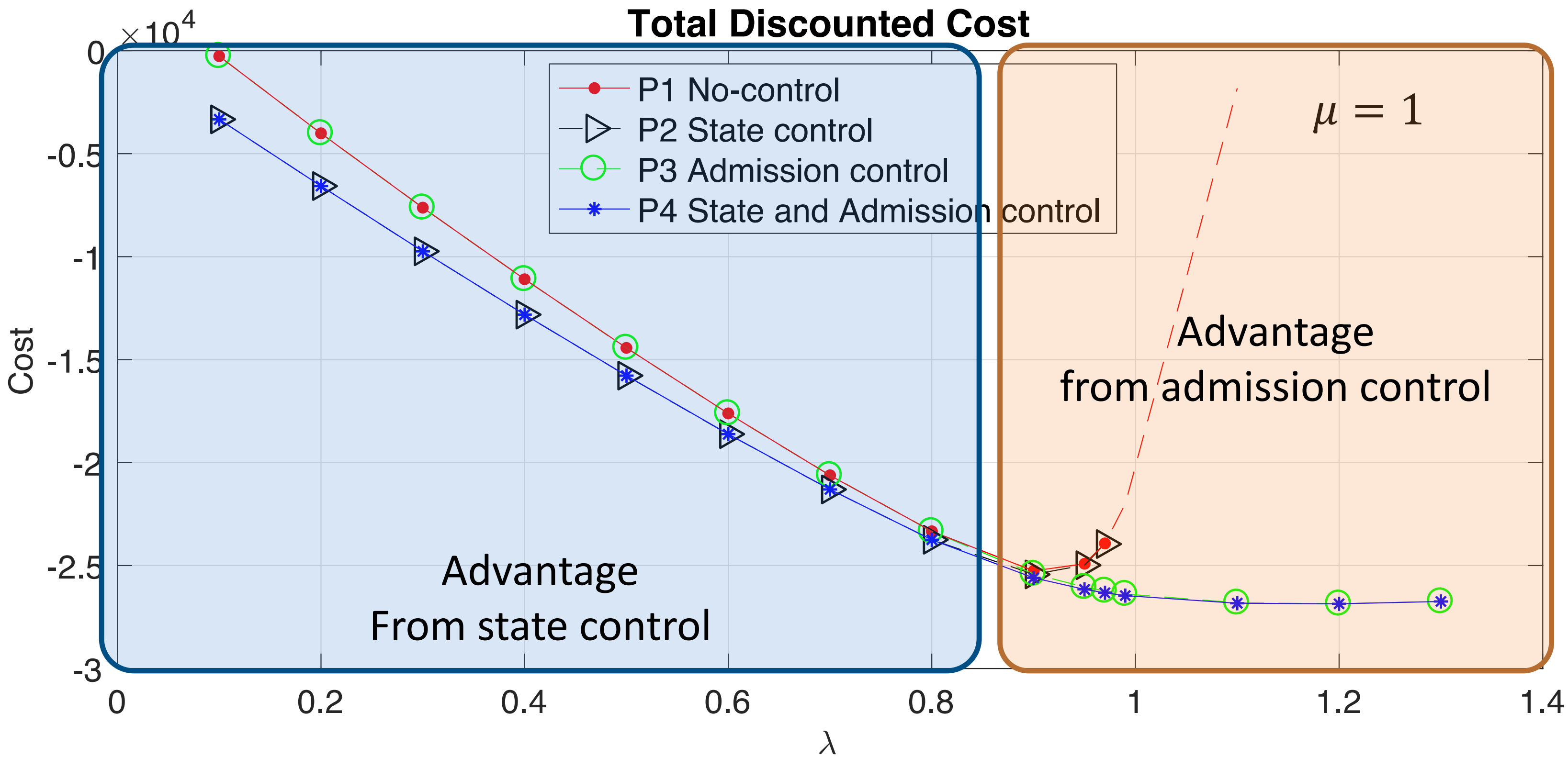




Arrival Rate with $w_q > 0$

$c_{out} = 0$
$c_{on} = 1$
$c_{su} = 1.91$
$c_{work} = 5.18$
$w_q = 0.07$

$t_p = 1$
$t_{su} = 0.23$
$r = 15$
$c_r = 0$
$\alpha = 10^{-5}$

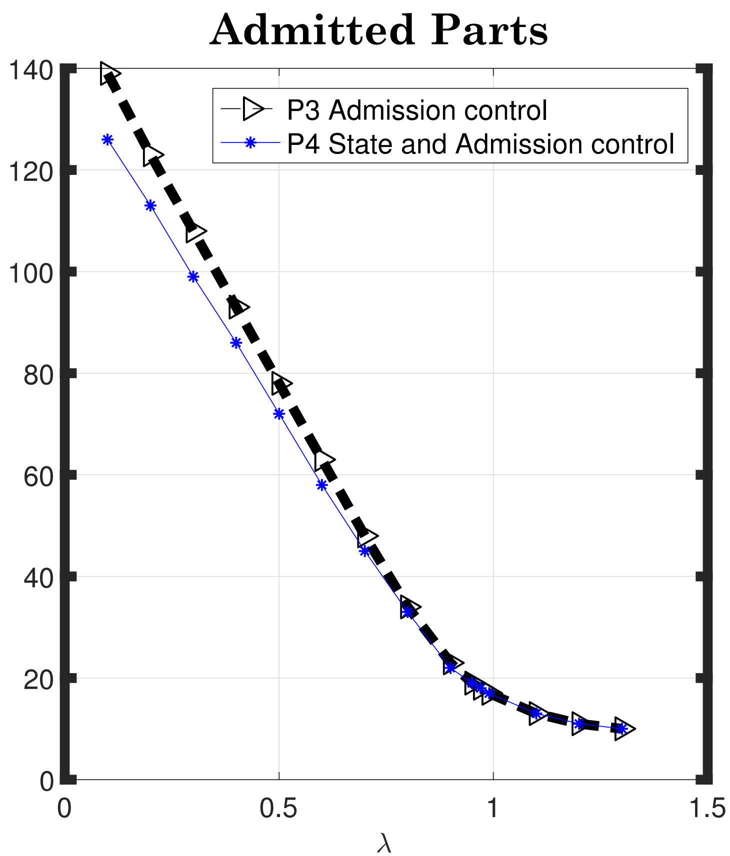


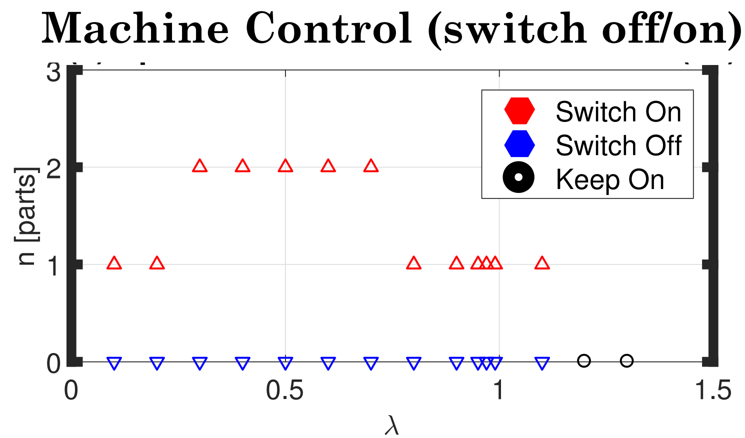
With $\lambda < 0.8$, savings are related to the machine control (switch off/on). For high utilization, savings are related to the admission control that limits the queue length.

Arrival Rate with $w_q > 0$

$c_{out} = 0$
$c_{on} = 1$
$c_{su} = 1.91$
$c_{work} = 5.18$
$w_q = 0.07$

$t_p = 1$
$t_{su} = 0.23$
$r = 15$
$c_r = 0$
$\alpha = 10^{-5}$





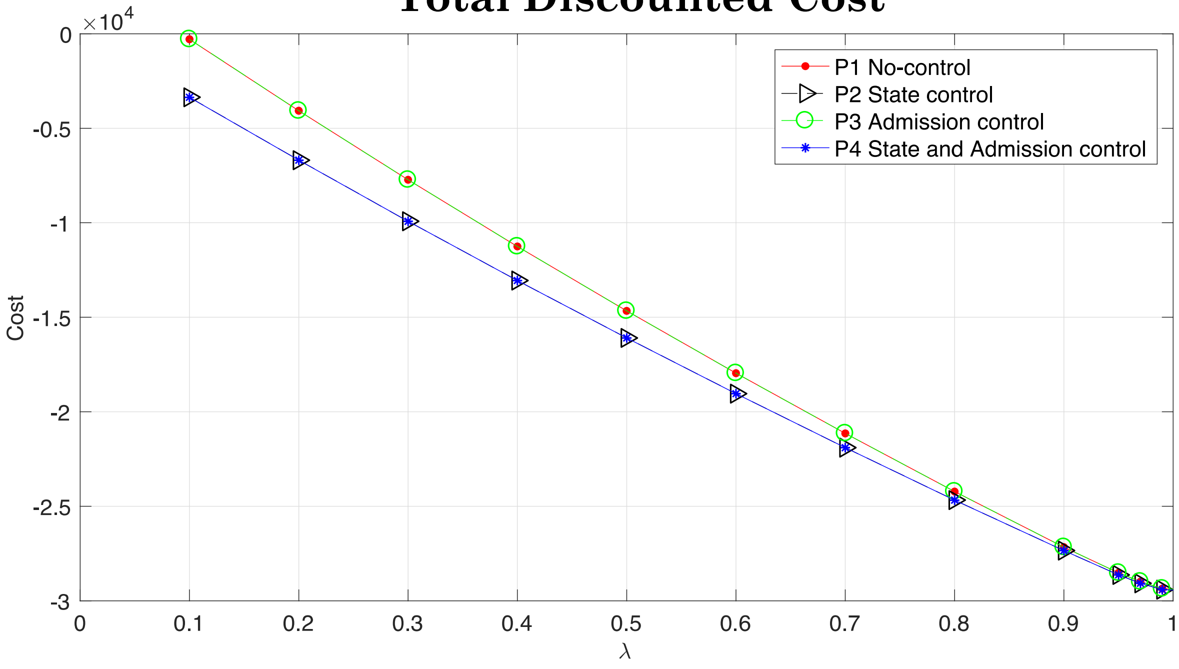
Arrival Rate with $w_q = 0$

$c_{out} = 0$
$c_{on} = 1$
$c_{su} = 1.91$
$c_{work} = 5.18$
$w_q = 0$

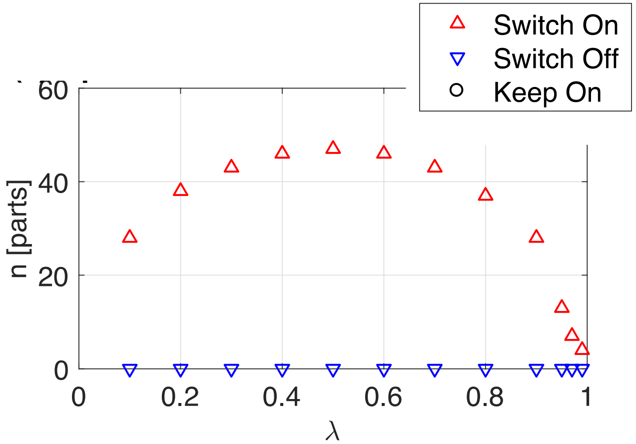
$t_p = 1$
$t_{su} = 0.23$
$r = 15$
$c_r = 0$
$\alpha = 10^{-5}$

- All parts are admitted

Total Discounted Cost



Machine Control (switch off/on)



Conclusions

1) A dynamic programming methodology has been used to model a machine tool with start/stop feature and requiring a startup, that is working in a production environment where the admission of parts is controlled.

2) Integration of productivity and sustainability criteria in the operation of manufacturing systems:
    - Structural property have been shown numerically;
    - Results are aligned with the common practice.

a) Future results will be devoted to:
    - Prove analytically the results of this work;
    - Adding a control of machine service rate;
    - Multiple Machine “Sleeping” States.

Thank You for Your Attention

Any question or remark?

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