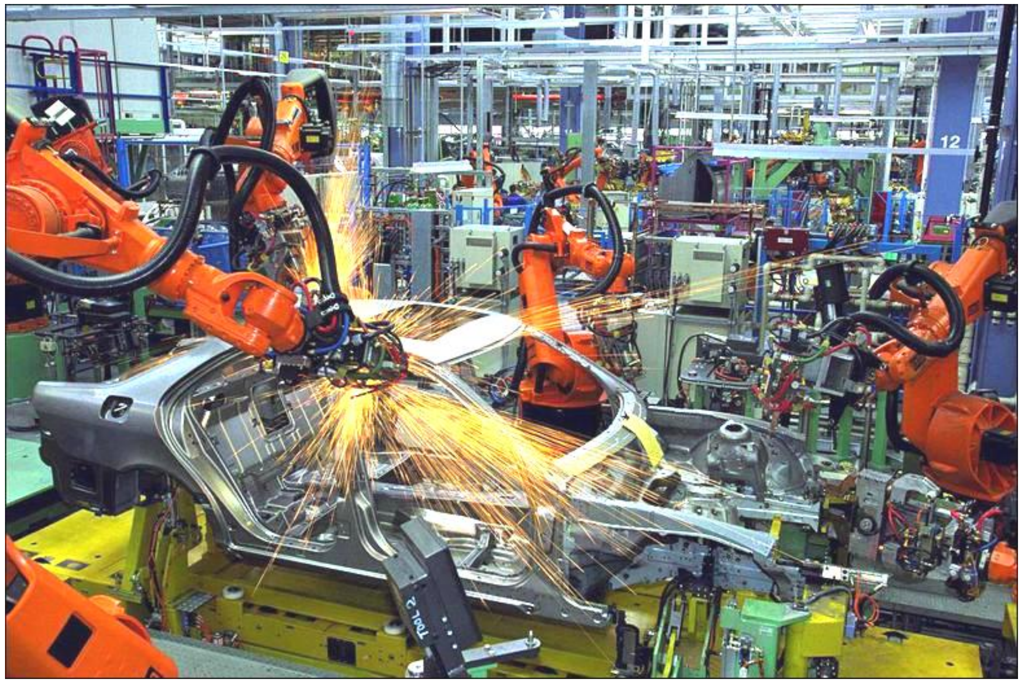
Optimization of power consumption for robotic lines in automotive industry



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Our Group

- **Industrial Informatics Group** (leaded by prof. Zdeněk Hanzálek)
- 4 permanent members, 2 post-docs, 7 Ph.D. students and 10 MSc. students
- **scheduling**, combinatorial optimization algorithms, real-time control systems and industrial communication protocols and parallel computing on graphics cards (i.e. GPU computing)
- we participated in many **European projects**, namely ARTIST2 - Network of Excellence on Embedded Systems Design (IST FP6), DEMANES (ARTEMIS FP7), and many others (US Navy, EUREKA).
- Close cooperation with **industry** (Skoda, UniControls, UNIS, Volkswagen, Rockwell, Air Navigation Services, Porsche)

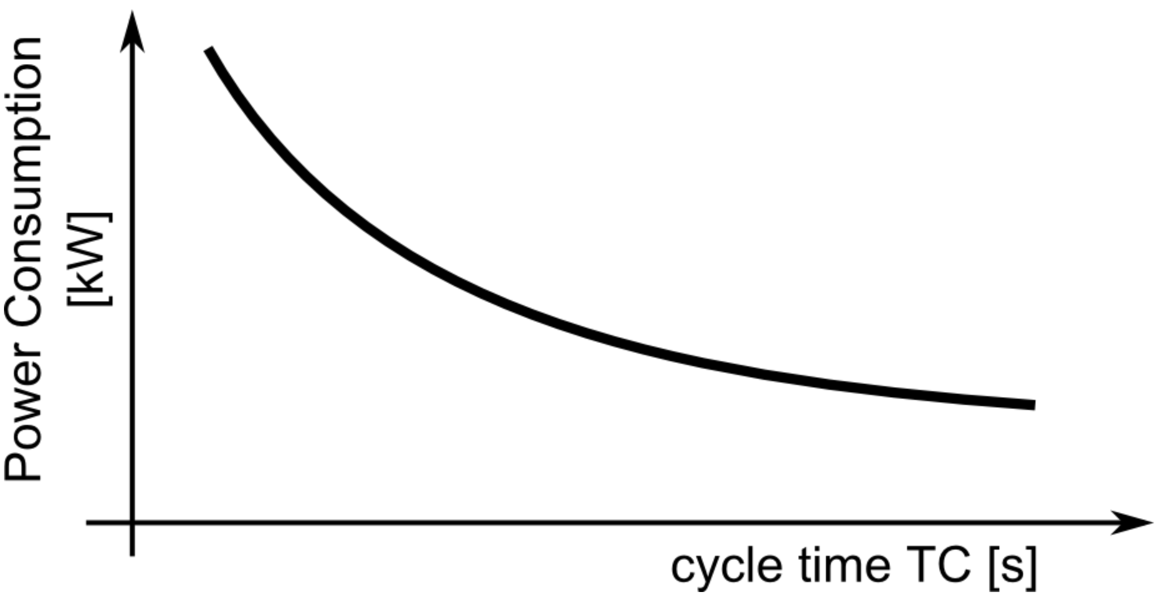
Motivation

- cooperation with **Škoda Auto** (contract paid by Škoda Auto)
- **energy consumption** minimization for robotic lines (welding)
- even small energy consumption reduction (**1%**) can save a lot of money

A robotic line in Škoda Auto

Motivation

- significant savings can be achieved by using modern control systems and **global optimization**
- **trade off** between cycle time and power consumption



Existing Works

- works in this area usually deal with **cycle time** [Wigstrom et al. 2013, Vergnano et al. 2012]
- energy optimization usually deals with **individual trajectories** [Lampariello et al. 2011, Michna et al. 2010]
- similar work is [Wigstrom et al. 2013, Michna et al. 2010, Vergnano et al. 2012] however several **aspects are not considered**

[Lampariello et al. 2011] - Lampariello, R.; Duy Nguyen-Tuong; Castellini, C.; Hirzinger, G.; Peters, J., "Trajectory planning for optimal robot catching in real-time," Robotics and Automation (ICRA), 2011 IEEE International Conference on , vol., no., pp.3719,3726, 9-13 May 2011.

[Wigstrom et al. 2013] - Wigstrom, O.; Lennartson, B.; Vergnano, A.; Breitholtz, C., "High-Level Scheduling of Energy Optimal Trajectories," Automation Science and Engineering, IEEE Transactions on , vol.10, no.1, pp.57,64, Jan. 2013.

[Michna et al. 2010] - Michna, V.; Wagner, P.; Cernohorsky, J., "Constrained optimization of robot trajectory and obstacle avoidance," Emerging Technologies and Factory Automation (ETFA), 2010 IEEE Conference on , vol., no., pp.1,4, 13-16 Sept. 2010.

[Vergnano et al. 2012] - Vergnano, A.; Thorstensson, C.; Lennartson, B.; Falkman, P.; Pellicciari, M.; Leali, F.; Biller, S., "Modeling and Optimization of Energy Consumption in Cooperative Multi-Robot Systems," Automation Science and Engineering, IEEE Transactions on , vol.9, no.2, pp.423,428, April 2012

Robot Energy Consumption

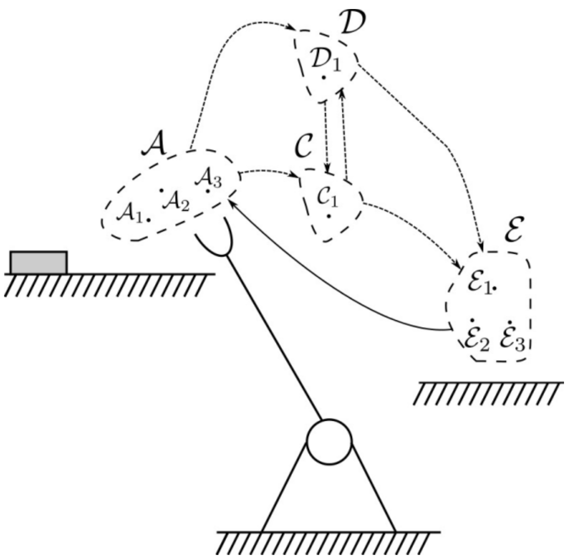
- **Analysis of energy consumptions** of a robot (KUKA KR 5 arc) using a HW developed at our department
- revealed the following **categories of saving**:

1. stationary positions selection
2. power save modes
3. trajectory selection
4. speed of movement
5. order of operations

Robot Energy Consumption

1) **stationary positions selection**

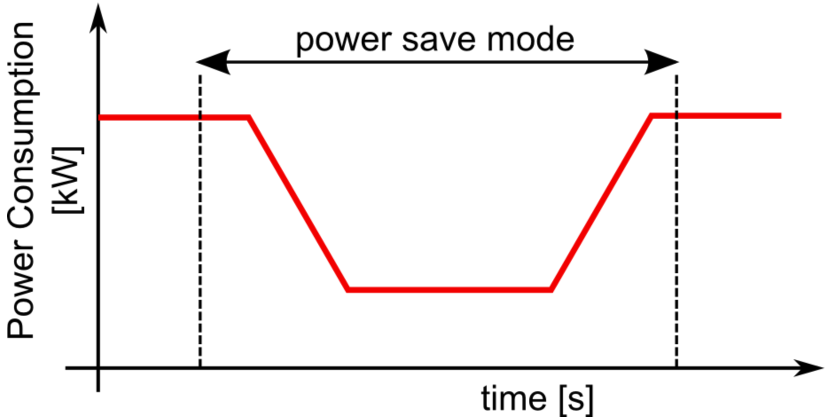
- decides where individual operations can be performed
- possible saving = 6% (without load)



Robot Energy Consumption

2) **power save modes**

- modes of position control (motors, brakes, bus power off, hibernate)
- setup time of power save modes must be taken into account
- possible saving = 45% (without load)



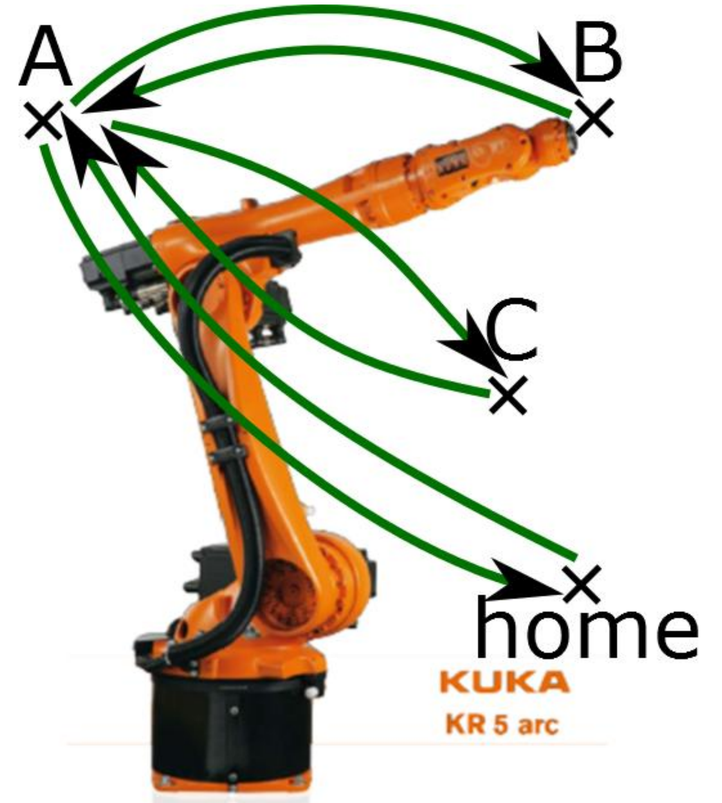
Robot Energy Consumption

3) **trajectory selection**

- decides how to move from point to point or how to avoid an obstacle
- possible saving depends on the problem instance

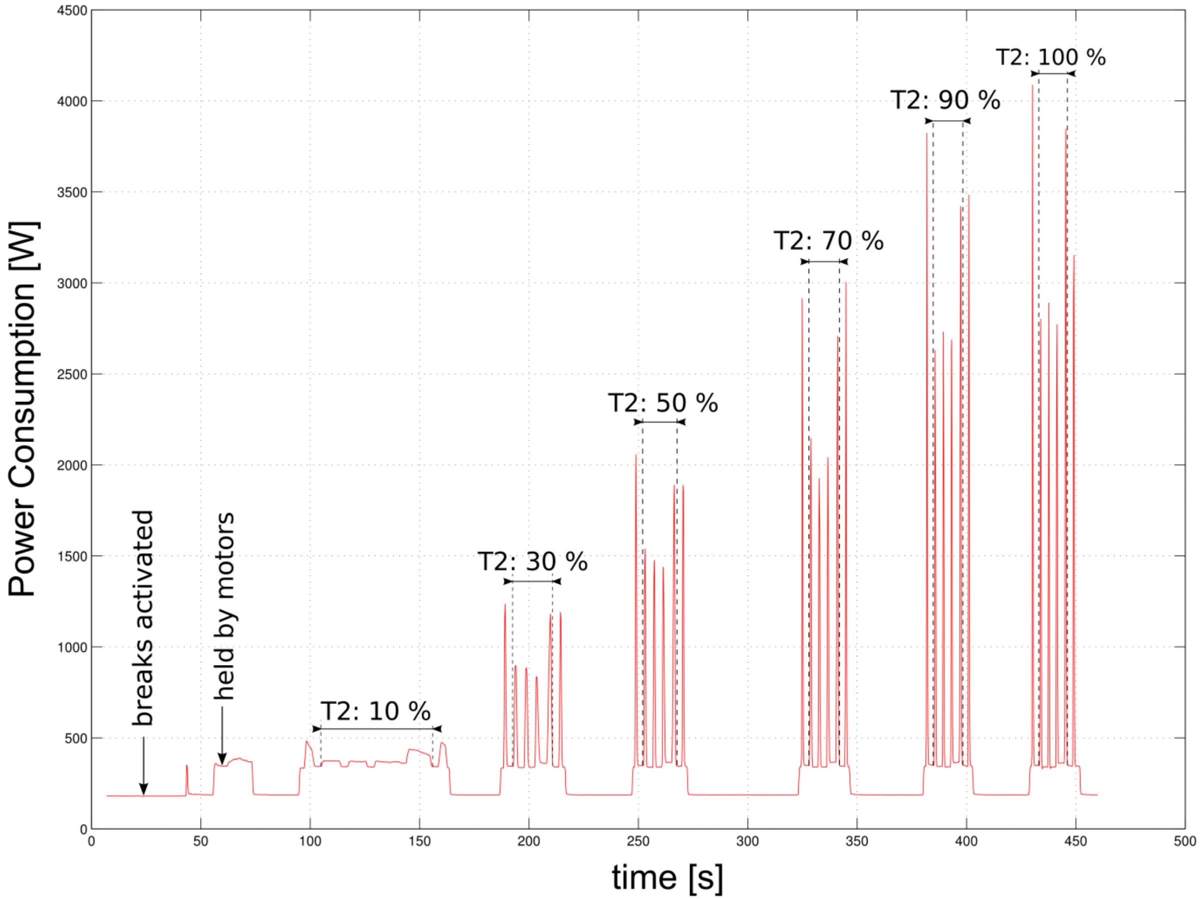
4a) **speed of movement**

- experiment with different trajectories
- possible saving depends on the trajectory



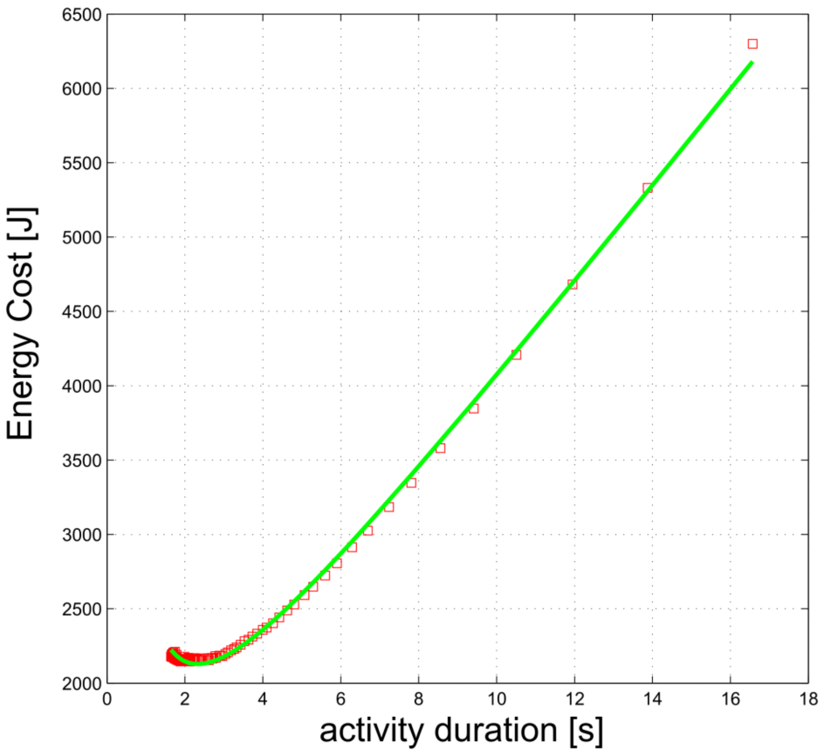
Robot Energy Consumption

4b) **speed of movement** – measurement of the KUKA KR5 arc robot



Energy Functions

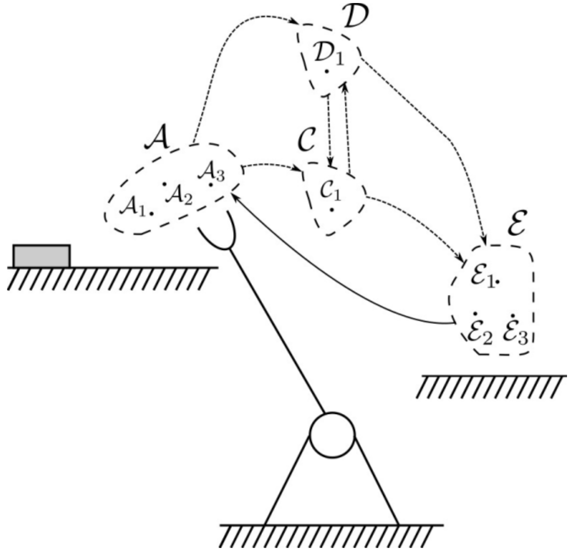
- dependence of **time of movement on energy consumption**
- interpolated by function $E(d_i) = \frac{a}{d_i} + bd_i + c$
- considered **convex energy functions**



Robot Energy Consumption

5) **order of operations**

- classical scheduling problem
- possible saving depends on the problem instance

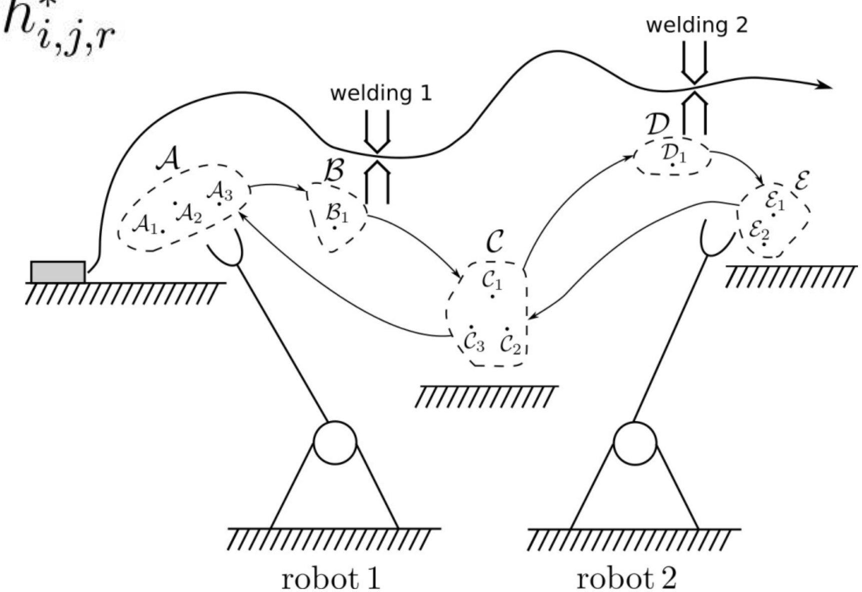


All the aspect can be considered in a single mathematical model

Mathematical Model

- mathematical model of a single robot is based on **Cyclic scheduling** [Hanen et al. 1995]

$$s_j - s_i = d_i - \mathrm{CT} h^*_{i,j,r}$$



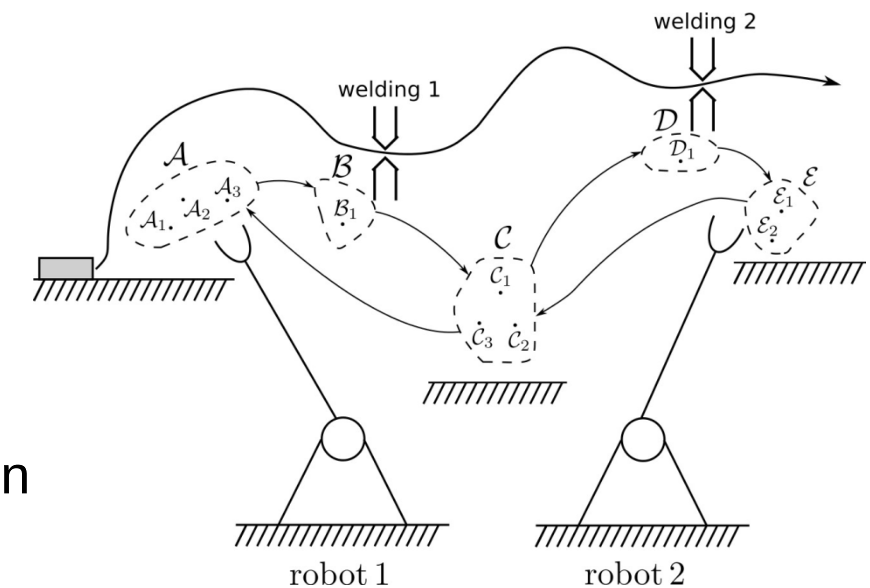
- s_i is activity start time
- d_i is duration of activity i
- CT is cycle time
- $h^*_{i,j,r}$ is height of the constraint

[Hanen et al. 1995] C. Hanen and A. Munier. A study of the cyclic scheduling problem on parallel processors. Discrete Applied Mathematics, 57:167–192, February 1995.

Mathematical Model

- synchronization between robots is based on positive and negative **time-lags** [Reyck et al. 1996]

$$s_j - s_i \geq l_{i,j} \quad \forall e \in E$$



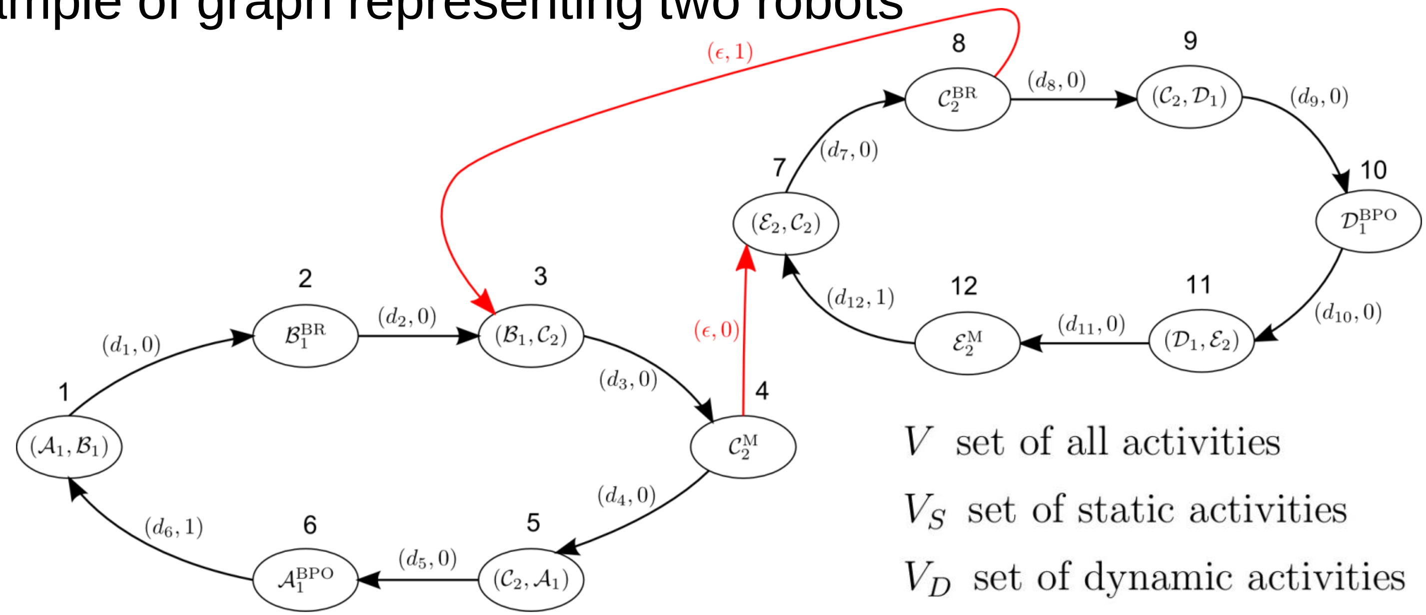
- $l_{i,j}$ is positive/negative time lag

- two possibilities of synchronization
  - robot 2 robot
  - bench

[Reyck et al. 1996] B. De Reyck, W. Herroelen, A branch-and-bound procedure for the resource-constrained project scheduling problem with generalized precedence relations Research Report, Katholieke Universiteit Leuven (1996)

Mathematical Model

- an example of graph representing two robots



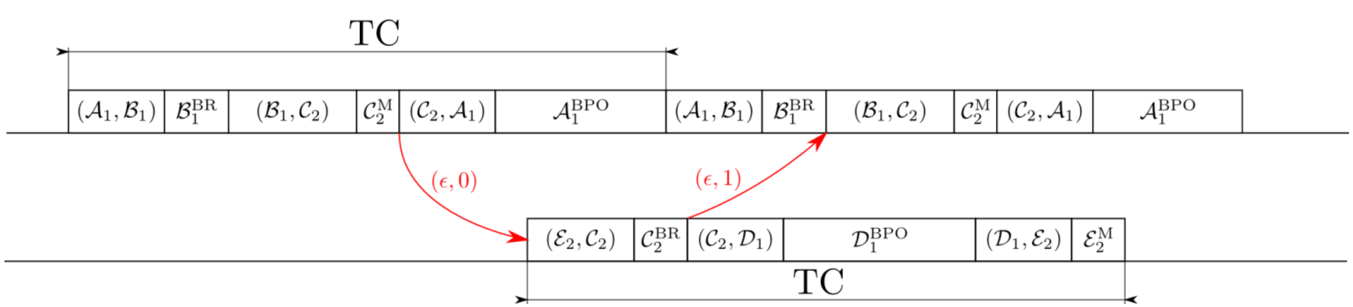
V set of all activities

V_S set of static activities

V_D set of dynamic activities

$$V = V_S \cup V_D$$

- a schedule



MILP Model

- for each node we introduce the following variables

W_i required energy by activity i

s_i start time of activity i

d_i duration of activity i

- for static nodes there are two decision variables

x_i^p true if point $p \in P_i$ of static activity i is selected

z_i^m true if the robot's mode $m \in M_i$ is selected in static activity i

- for dynamic activities there is

y_i^t true if movement $t \in T_i$ of dynamic activity i is selected

$$W_i, s_i, d_i \in \mathbb{R}_0^+ \quad x_i^p, z_i^m, y_i^t, h_{i,j,r}^*, w_{i,j} \in \mathbb{B}$$

MILP Model

$$\text{minimise} \quad \sum_{\forall i \in V} W_i$$

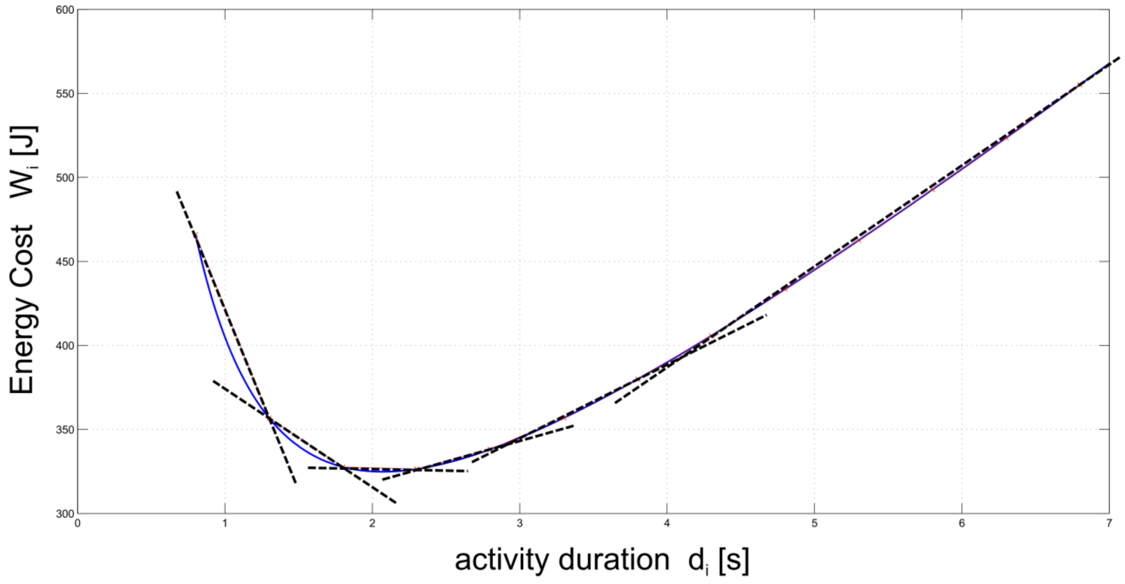
$$s.t. \quad a_{i,p}^{m} d_i - \overline{W}\left(2 - z_i^m - x_i^p\right) \le W_i \qquad (1)$$

$$\forall i \in V_S, \forall p \in P_i, \forall m \in M_i$$

$$a_{i,k}^{t} d_i + b_{i,k}^{t} - \overline{W}\left(1 - y_i^t\right) \le W_i \qquad (2)$$

$$\forall i \in V_D, \forall t \in T_i, \forall k \in K$$

energy functions



MILP Model

$$\text{minimise} \sum_{\forall i \in V} W_i$$

$$s.t. \quad a^m_{i,p} d_i - \overline{W}\left(2 - z^m_i - x^p_i\right) \leq W_i \qquad \forall i \in V_S, \forall p \in P_i, \forall m \in M_i \tag{1}$$

$$a^t_{i,k} d_i + b^t_{i,k} - \overline{W}\left(1 - y^t_i\right) \leq W_i \qquad \forall i \in V_D, \forall t \in T_i, \forall k \in K \tag{2}$$

$$\sum_{\forall p \in P_i} x^p_i = 1 \qquad \forall i \in V_S \tag{3}$$

$$\sum_{\forall m \in M_i} z^m_i = 1 \qquad \forall i \in V_S \tag{4}$$

$$\sum_{\forall t \in T_i} y^t_i = 1 \qquad \forall i \in V_D \cap V_{\mathcal{M}} \tag{5}$$

$$\sum_{\forall j \in \text{PRED}(i)} \sum_{\forall t \in T_j(p_{\text{from}}, p)} y^t_j = x^p_i \qquad \forall i \in V_S, \forall p \in P_i \tag{6}$$

$$\sum_{\forall j \in \text{suc}(i)} \sum_{\forall t \in T_i(p, p_{\text{to}})} y^t_j = x^p_i \qquad \forall i \in V_S, \forall p \in P_i \tag{7}$$

$$s_j - s_i + (1 - w_{i,j})\,\text{CT} \geq d_i - \text{CT}h^*_{i,j,r} \qquad \forall r \in R, \forall i \in V_{\mathcal{O}} \cap V_r \cap V_D, \forall j \in \text{suc}(i) \tag{10}$$

$$s_j - s_i - (1 - w_{i,j})\,\text{CT} \leq d_i - \text{CT}h^*_{i,j,r} \qquad \forall r \in R, \forall i \in V_{\mathcal{O}} \cap V_r \cap V_D, \forall j \in \text{suc}(i) \tag{11}$$

$$\sum_{\forall i,j} h^*_{i,j,r} = 1 \qquad \forall r \in R \tag{12}$$

$$\underline{d}^m z^m_i \leq d_i \leq \overline{d_i} \qquad \forall i \in V_S, \forall m \in M_i \tag{13}$$

$$\underline{d^t_i} y^t_i \leq d_i \leq \overline{d^t_i} + \text{CT}\left(1 - y^t_i\right) \qquad \forall i \in V_D, \forall t \in T_i \tag{14}$$

$$h^*_{i,j,r} = 0 \qquad \forall r \in R, \forall i \in V, \forall j \notin V_{\text{IN}} \tag{15}$$

$$s_j - si \geq l_{i,j} - \text{CT}h_{i,j} \qquad \forall e \in E \tag{16}$$

$$x^p_i \leq \sum_{\forall p' \in \text{CP}(i,p)} x^{p'}_j \qquad \forall i, j \subseteq V_{\text{OUT}} \times V_{\text{IN}} \tag{17}$$

$$W_i, s_i, d_i \in \mathbb{R}^+_0 \quad x^p_i, z^m_i, y^t_i, h^*_{i,j,r}, w_{i,j} \in \mathbb{B}$$

Lagrangian Relaxation

- to obtain good lower bound the Lagrangian relaxation was used
- constraints (16) and (17) relaxed, **decomposition to individual robots**

$$\underset{\substack{\lambda_e \geq 0 \\ \alpha \geq 0}}{\text{maximise}} \quad \underset{\substack{W_i, s_i, d_i \in \mathbb{R}_0^+ \\ x_i^p, z_i^m, y_i^t, h_{i,j,r}^*, w_{i,j} \in \mathbb{B}}}{\text{minimise}} \quad \sum_{\forall i \in V} W_i + \sum_{\forall e \in E} \lambda_e \left(l_{i,j} - \mathrm{CT} h_{i,j} + s_i - s_j \right) + \sum_{\forall i,p} \alpha_{i,p} \left(x_i^p - \sum_{\forall p' \in \mathrm{CP}(i,p)} x_j^{p'} \right)$$

$$\text{subject to (1) to (15)}$$

- dual Lagrangian task solved by the sub-gradient algorithm
- very tight lower bound (see experimental results)

Experimental Results

- **server configuration**
  - 2 x Intel Xeon E5-2620 v2 @ 2.10GHz (12 cores in total), 64 GB RAM
  - Gentoo Linux 2014, IBM Ilog Cplex 12.6

- **generated instances**
  - 5 robots, 3 power save modes (motors, brakes, bus-power-off), from 1 to 4 points for each static activity, fixed production cycle time, approx. 150 activities per instance
  - energy functions based on measured data of KUKA KR 5 arc robot

Experimental results

- **MILP model**
  - 17 feasible instances, approx. 10 000 constraints and 1 000 variables

	time limit 100 s	time limit 7200 s
min Energy Cost (ΣW_i)	28 038.8 J	27656.2 J
avg Energy Cost (ΣW_i)	33 796.7 J	32681.6 J (improved about 3.3 %)
max Energy Cost (ΣW_i)	43 043.0 J	40849.9 J

  - average proved Cplex gap 27.5 % (7200 seconds time limit)
- **Lagrangian relaxation**
  - very computationally expensive
  - very tight lower bound (3.5 % gap to the best proved Cplex upper bounds)
  - Lagrangian relaxation gives much tighter lower bounds than Cplex (3.5 % vs. 27.5 % gap)

Conclusion and Future Work

- Conclusion
  - analysis of energy consumption of robots taking into account **power save modes**
  - **Improved mathematical formulation** of energy consumption optimization for robotic lines ([Vergnano et al. 2012])
  - Lagrangian relaxation based **lower bound**

- Current work
  - experiments with real data from Škoda Auto
  - propose faster lower bound(s)

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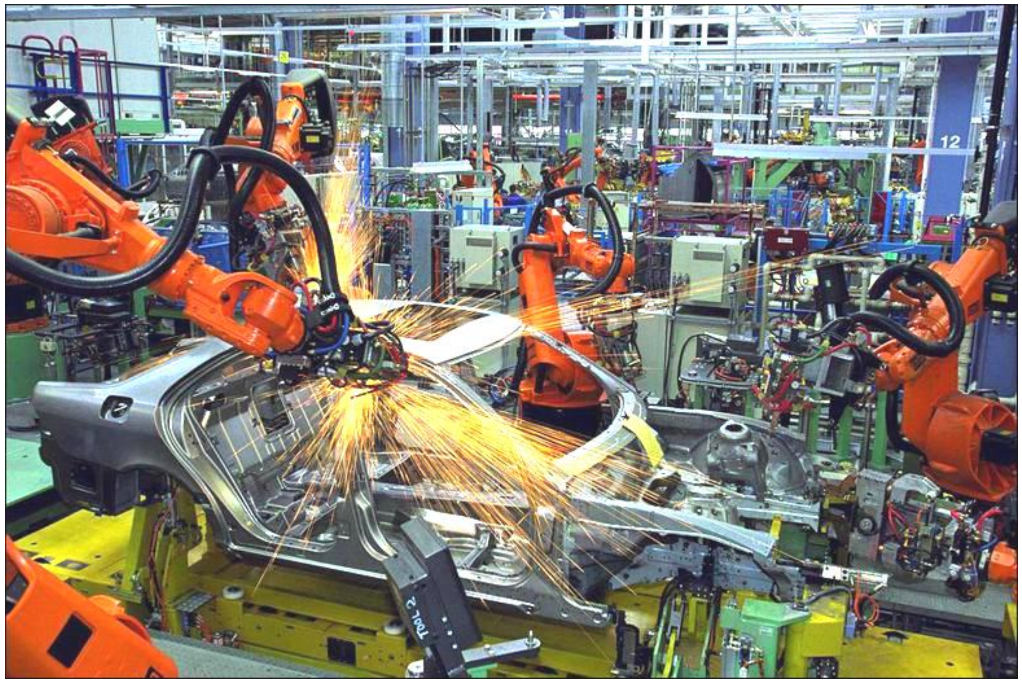

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