Energy Considerations in a Two Machine Flowshop Scheduling Problem with Sequence Dependent Setups

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Outline

1. Motivation
   - Sustainable manufacturing
   - Flowshop problem with total energy consumption
   - Previous work
2. Methodology
   - Mathematical formulation
   - Multiobjective genetic algorithm
   - Data
3. Work in progress
   - Main results and contribution
   - Future work
4. Summary

Outline

Sustainability concerns in manufacturing

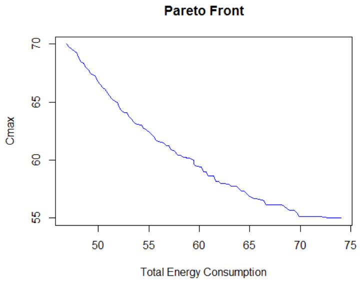
- Challenges
  - Increasing costs
  - Scarcity of energy, resources, and material
- Manufacturing sector major contributor to the UK economy
  - The third largest sector
  - Over 11% of the national economy
  - Over 8% of total UK employment
- Transition to a low-carbon economy
- Energy considerations for resource efficient manufacturing

Outline

Background

$$F2|ST_{sd}|C_{max}, \text{Energy}$$

- Multiple products
- Different running speeds
- Two machine sequence dependent permutation flowshop problem
- Conflicting criteria: C_{max} and total energy consumption (TEC)



Outline

Flowshop scheduling with sequence dependent setups

- Two machine sequence dependent flowshop problem
  - A variation of TSP
  - Can be solved for C_{max} with Johnson's algorithm if the setup times are not sequence dependent
- Survey on scheduling problems with setup times / costs [1]

Energy consumption

- Minimizing Total Energy Consumption and Total Completion Time [2]
- Energy consumption characteristics driven by task flow in machining [3]
- Energy consumption model and energy optimization in manufacturing [4]

Multiobjective Genetic Algorithms

- Multicriteria scheduling [5]
- Application of GA on scheduling problems with multiple objectives [6, 7, 8]
- Multi-objective optimization by means of GAs [9, 10]

Outline

Parameters

N	=	number of jobs; $j = 1, \ldots, N$
M	=	number of machines; $i = 1, \ldots, M$
p_{ij}	=	processing time of job j on machine i
v_l	=	processing speed factor (same for all machines: slow, normal, fast)
s_{ijk}	=	sequence dependent setup time of changing over from job j to job k on machine i
π	=	a very large number
$conv_l$	=	conversion factor for processing speed (converts time to energy unit depending on speed)
$idleconv_i$	=	conversion factor for idle time on machine i
r	=	iteration controller

Positive variables

c_{ij} = latest completion time of job j on machine i

fc_j = setup and completion time correction for the first job on second machine

$idle_i$ = idle time on machine i

TEC = total energy consumption

Binary variables

$$f_j = \begin{cases} 1 & \text{if job } j \text{ is the first job,} \\ 0 & \text{otherwise.} \end{cases}$$

$$x_{jk} = \begin{cases} 1 & \text{if job } j \text{ is scheduled any time before job } k, \\ 0 & \text{otherwise.} \end{cases}$$

$$t_{jk} = \begin{cases} 1 & \text{if job } j \text{ is scheduled immediately before job } k, \\ 0 & \text{otherwise.} \end{cases}$$

$$y_{ijl} = \begin{cases} 1 & \text{if job } j \text{ is processed at speed } l \text{ on machine } i, \\ 0 & \text{otherwise.} \end{cases}$$

Objective function and timing constraints

$$\min C_{max} \tag{1}$$

$$c_{1j} \geq p_{1j}/v_l \times y_{1jl} + s_{1jj} \times f_j \qquad \forall j \qquad \forall l \tag{2}$$

$$\pi \times (1 - f_j) + fc_j \geq s_{2jj} - c_{1j} \qquad \forall j \tag{3}$$

$$c_{2j} \geq c_{1j} + fc_j + p_{2j}/v_l \times y_{2jl} \qquad \forall j \qquad \forall l \tag{4}$$

$$\pi \times f_k + \pi \times (1 - t_{jk}) + c_{ik} \geq c_{ij} + p_{ik}/v_l \times y_{ikl} + s_{ijk} \times t_{jk} \qquad \forall i \qquad \forall j \qquad \forall k \qquad \forall l \qquad j \neq k \tag{5}$$

$$c_{max} \geq c_{2j} \qquad \forall j \tag{6}$$

Balance constraints

$$\sum_{j} f_j = 1 \tag{7}$$

$$\sum_{l} y_{ijl} = 1 \qquad \forall i \qquad \forall j \tag{8}$$

$$\sum_{k} t_{jk} = 1 \qquad \forall j \qquad j \neq k \tag{9}$$

$$\sum_{j} t_{jk} = 1 \qquad \forall k \qquad j \neq k \tag{10}$$

Energy constraints

$$idle_i = c_{max} - \sum_j \sum_l p_{ij} / v_l \times y_{ijl} \quad (11)$$

$$TEC_r = \sum_{i,j,l} conv_l \times p_{ij} / v_l \times y_{ijl} + \sum_i idle_i \times idleconv_i \quad (12)$$

$$TEC_r \leq TEC_{r-1} - \epsilon \quad (13)$$

Outline

- Chromosome structure: 2D [11]

Job string:	J1	J2	...	Jn
Speed on Machine 1:	y_{11l}	y_{12l}	...	y_{1nl}
Speed on Machine 2:	y_{21l}	y_{22l}	...	y_{2nl}

- Based on non-dominated sorting [10]
- Elitist strategy
- Genetic operators
  - Order cross-over for recombination
  - Inversion, insertion, and swap operators for diversification

input : Search parameters
output: A nondominated set

Let time counter $t = 0$;
Initialize search parameters;
Let $\{Elite\ Set\} = \emptyset$;
while $t < t_{max}$ **do**
    Perform nondominated sorting and niching;
    Select individuals for *mating pool*;
    From *mating pool*, generate *new generation* using genetic operators;
    Let *current generation = new generation*;
    Identify F^1 = nondominated frontier of *current generation*;
    Let $\{Elite\ Set\} = \{Elite\ Set\} \cup F^1$;
    Refine $\{Elite\ Set\}$;
    Let $t = t + 1$;
end
Report *{Elite Set}*;

- Population size = $4 \times N$
- Maximum execution time = $5 \times N$ seconds
- Crossover rate = 0.7
- Inversion rate = 0.10
- Mutation rate = 0.10
  - Insertion rate = 0.80
  - Swap rate = 0.20
- Initial population is generated randomly
- Approach for fine tuning: Compare the result of MOGA with CPLEX frontier

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Data example

N:	4
M:	2
L:	3

p_{j1}:	8	6	9	4
p_{j2}:	1	5	5	9

v_l:	1.2	1	0.8
$Conv_l$:	1.5	1	0.6
$IdleConv_i$:	0.05	0.15	

S_{1jk}:

9	19	15	6
11	17	16	6
5	3	8	4
8	4	7	16

S_{2jk}:

6	10	1	7
4	7	7	4
9	9	7	2
10	1	5	7

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Initial runs: MOGA (35 sec); MIP (2610 sec)

Contribution

- Mathematical formulation for inclusion of energy consumption in the $F2|ST_{sd}|C_{max}$
- Lower bound on C_{max}
  1. $p_{ij}^{C_{max}^{LB}} = p_{ij}/v_1 + \max(s_{ijk} \in S)$
  2. Run Johnson's algorithm to find C_{max}^{LB}
- Lower bound on TEC
  1. $p_{ij}^{C_{max}^{UB}} = p_{ij}/v_3 + \max(s_{ijk} \in S)$
  2. Run Johnson's algorithm to find C_{max}^{UB}
  3. $idle_i^{C_{max}^{UB}} = C_{max}^{UB} - \sum_i \sum_j p_{ij}/v_3$
  4. $TEC_{LB} = \sum_{i,j} conv_3 \times p_{ij}/v_3 + \sum_i idle_i^{C_{max}^{UB}} \times idleconv_i$

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Test with real problem: Biscuit Manufacturer

- Core markets: United Kingdom, Netherlands, France, Belgium, Ireland
- Size: >5K employees
- Strategy: minimize impact on the environment

Test with real problem: Biscuit Manufacturer

Baking oven: a traveling conveyor belt 18 biscuit wide, 80m long

Energy to bake one tonne of biscuits may change by up to 25%

- Line process rate which may be driven by pack size
- Changeovers (ie milk to plain chocolate) pause the process
- Level of waste

Summary

- C_{max} a measure of service
- *TEC* a measure of sustainability
- Facilitation of trade-off analysis

- Outlook
  - Comparison of MOGA with CPLEX on various problems
  - Lower Bounds on C_{max} and *TEC*
  - MOGA as a decision support tool for trade-off analysis

References I

[1] Ali Allahverdi, C.T. Ng, T.C.E. Cheng, and Mikhail Y. Kovalyov. A survey of scheduling problems with setup times or costs. *European Journal of Operational Research*, 187(3):985 – 1032, 2008. ISSN 0377-2217. doi: 10.1016/j.ejor.2006.06.060. URL http://www.sciencedirect.com/science/article/pii/S0377221706008174.

[2] M. B. Yildirim and G. Mouzon. Single-machine sustainable production planning to minimize total energy consumption and total completion time using a multiple objective genetic algorithm. *Engineering Management, IEEE Transactions on*, PP (99):1 –13, 2011. ISSN 0018-9391. doi: 10.1109/TEM.2011.2171055.

[3] Yan He, Bo Liu, Xiaodong Zhang, Huai Gao, and Xuehui Liu. A modeling method of task-oriented energy consumption for machining manufacturing system. *Journal of Cleaner Production*, 23(1):167 – 174, 2012. ISSN 0959-6526. doi: 10.1016/j.jclepro.2011.10.033. URL http://www.sciencedirect.com/science/article/pii/S0959652611004197.

[4] A. Dietmair and A. Verl. A generic energy consumption model for decision making and energy efficiency optimisation in manufacturing. *International Journal of Sustainable Engineering*, 2(2):123–133, 2009.

References II

[5] V. T'kindt and J.C. Billaut. *Multicriteria scheduling: theory, models and algorithms*. Springer, 2006.

[6] SG Ponnambalam, H. Jagannathan, M. Kataria, and A. Gadicherla. A tsp-ga multi-objective algorithm for flow-shop scheduling. *The International Journal of Advanced Manufacturing Technology*, 23(11):909–915, 2004.

[7] T. Pasupathy, C. Rajendran, and RK Suresh. A multi-objective genetic algorithm for scheduling in flow shops to minimize the makespan and total flow time of jobs. *The International Journal of Advanced Manufacturing Technology*, 27(7): 804–815, 2006.

[8] S. Deva Prasad, OV Krishnaiah Chetty, and C. Rajendran. A genetic algorithmic approach to multi-objective scheduling in a kanban-controlled flowshop with intermediate buffer and transport constraints. *The International Journal of Advanced Manufacturing Technology*, 29(5):564–576, 2006.

[9] C.A.C. Coello, G.B. Lamont, and D.A. Van Veldhuisen. *Evolutionary Algorithms for Solving Multi-Objective Problems*. Genetic and Evolutionary Computation Series. Springer, 2007. ISBN 9780387367972. URL `http://books.google.co.uk/books?id=rXIuAMw3lGAC`.

References III

[10] K. Deb. *Multi-Objective Optimization Using Evolutionary Algorithms*. Wiley-Interscience series in systems and optimization. John Wiley & Sons, 2009. ISBN 9780470743614. URL http://books.google.co.uk/books?id=U0dnPwAACAAJ.

[11] Z. Michalewicz. *Genetic Algorithms + Data Structures = Evolution Programs*. Artificial intelligence. Springer, 1998. ISBN 9783540606765. URL http://books.google.co.uk/books?id=vlhLAobsK68C.