# OPTIMISATION OF ENERGY EFFICIENT ASSEMBLY SEQUENCE PLANNING USING MOTH-FLAME OPTIMISATION ALGORITHM

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**SUPERVISOR'S DECLARATION**

We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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# ABSTRAK

Dalam pengoptimuman pemasangan, perancangan turutan pemasangan (ASP) merujuk kepada aktiviti mencari kemungkinan rangkaian pemasangan terbaik yang dibangunkan berdasarkan pemodelan pemasangan. Masalah ini tergolong dalam kategori ketidakketentuan masa-polinomial (NP) sukar. Pada masa ini, masalah ini tidak dapat diselesaikan melalui pendekatan tepat. Memandangkan kerumitan pengoptimuman masalah ASP, pendekatan tradisional yang menilai penyelesaian ASP satu persatu tidak sesuai digunakan disebabkan jumlah masa, tenaga dan kos yang tinggi. Dalam ASP, kajian masalah pengoptimuman adalah penting untuk menentukan turutan pemasangan terbaik. Penyelidikan dalam ASP telah diberi banyak perhatian, terutamanya objektif yang berorientasikan keuntungan dan berkaitan manusia. Namun, berdasarkan kajian terdahulu, perhatian kurang diberikan untuk menangani isu kemanpanan dalam pemasangan seperti pelepasan karbon dan penggunaan tenaga. Di sisi lain, kajian ASP hari ini cenderung untuk meneroka potensi algoritma baru bagi mengoptimumkan ASP. Oleh itu, kajian ini bertujuan untuk membangunkan satu kaedah dan menggunakan algoritma bagi mengoptimumkan masalah pemasangan turutan perancangan dengan kecekapan tenaga (EE-ASP). Dalam model yang dicadangkan, penggunaan tenaga terbiar dioptimumkan bersama dengan arah dan alat pemasangan. Bagi tujuan pengoptimuman, penyelidikan ini menggunakan satu algoritma baru iaitu *Moth-Flame Optimisation* (MFO). Ujian berkomputer dilakukan dengan menggunakan enam masalah dari kajian terdahulu. Selain itu, kajian kes dijalankan untuk mengesah kebolehgunaan model EE-ASP dan prestasi algoritma untuk pengoptimuman. Prestasi MFO dibandingkan dengan tiga algoritma meta heuristik yang kerap digunakan di dalam ASP, iaitu *Ant Colony Optimisation* (ACO), *Genetic Algorithm* (GA) dan *Particle Swarm Optimisation* (PSO). Berdasarkan ujian berkomputer, MFO mencapai keputusan terbaik bagi kecergasan minima, kecergasan maksima, purata kecergasan dan sisihan piawai dalam setiap masalah ujian. Sementara itu, hasil kajian kes turut menunjukkan MFO memperolehi keputusan terbaik bagi kecergasan minima, kecergasan maksima dan purata kecergasan. Semua keputusan kemudian dianalisa menggunakan *Analysis of Variance* (ANOVA). Nilai P didapati lebih rendah berbanding aras signifikan α ($P \leq 0.10$) dalam setiap masalah ujian dan kajian kes. Oleh itu, terdapat perbezaan signifikan secara statistik antara purata kumpulan. Hasil dari ANOVA tadi, kemudian dianalisa dengan teknik *post-hoc Fisher's Least Significant Difference* (LSD). Keputusan LSD menunjukkan MFO memiliki perbezaan signifikan di dalam 67 % daripada kes-kes berbanding dengan algoritma perbandingan untuk masalah ujian. Keputusan dari kajian kes mengesahkan cadangan model EE-ASP dan algoritma MFO boleh diaplikasikan terhadap data pemasangan sebenar. Cadangan susun atur oleh MFO mampu mengurangkan penggunaan tenaga terbiar sehingga 11.7 %, sementara bilangan perubahan arah pemasangan dan alatan berkurangan masing-masing sebanyak 26.67 % dan 13.64 %. Hasil dari kajian dapat disimpulkan bahawa model penggunaan tenaga terbiar untuk ASP boleh digunakan sebagai garis panduan untuk mereka bentuk stesen bagi proses pemasangan yang mampan. Selain itu, MFO mempunyai potensi yang besar untuk terus diterokai bagi tujuan pengoptimuman masalah kombinatorial yang lain.

## ABSTRACT

In assembly optimisation, Assembly Sequence Planning (ASP) refers to the activity of finding the best possible assembly sequences developed on the foundation of assembly modelling. This problem is a non-deterministic polynomial-time (NP) hard problem, as currently cannot be solved by using a specific approach. By considering the complexity to optimise the ASP problem, the traditional approach that evaluates every single possible solution for ASP is inconvenient to be used due to time constraint, high energy consumed and computational cost. In ASP, the research on problem optimisation is important and needs an effective computational approach to determine the best assembly sequence. Research on ASP has been given a lot of attention, especially with the profit and human-related objectives. However, based on the literature survey, less attention was given to tackle the sustainable issue in assembly such as carbon emission and energy utilisation. On the other hand, the recent ASP research tends to explore the potential of a relatively new algorithm to optimise ASP. Therefore, the aim of this research is to establish a methodology and implement the relatively new algorithm to optimise the Energy Efficient Assembly Sequence Planning (EE-ASP) problem. In the proposed model, the idle energy utilisation was optimised together with the assembly direction and tool changes. For optimisation purpose, this research proposed a relatively new algorithm called the *Moth-Flame Optimisation* (MFO). A computational experiment was performed by using the six test problems from the literature. Furthermore, a case study was conducted to validate the proposed EE-ASP model and the performance of the optimisation algorithms. The MFO performance was compared with three frequently used meta-heuristics algorithms in ASP, namely *Ant Colony Optimisation* (ACO), *Genetic Algorithm* (GA) and *Particle Swarm Optimisation* (PSO). Based on the computational experiment, MFO achieved the best results in terms of minimum fitness, maximum fitness, average fitness, and standard deviation in each test problem. Meanwhile, the case study results also indicated that MFO obtained the best minimum fitness, maximum fitness and average fitness. All of the results were then analysed by using the *Analysis of Variance* (ANOVA) method. The P-value was found to be lower than the significant level $\alpha$ ($P \leq 0.10$) in all test and case study problems. Therefore, it could be interpreted that there were statistically significant differences among the group means. The outcomes of ANOVA for the test and case study problems were further analysed with the *post-hoc Fisher's Least Significant Difference* (LSD) technique. The LSD result indicated that the MFO had a significant difference in 67 % of the cases as compared to the comparison algorithms. The result from the case study confirmed that the proposed EE-ASP model and MFO algorithm were applicable for the actual assembly data. The proposed MFO layout was able to reduce the idle energy utilisation up to 11.7 %, while the direction change and tool change reduced to 26.67 % and 13.64 % respectively. The findings from this research concluded that the idle energy utilisation model for ASP can be used as a guideline to design a station for sustainable assembly process. Besides that, the MFO had a great potential to be further explored to optimise the combinatorial problem.

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**LIST OF SYMBOLS**

| | |
|---|---|
| α | Significant level |
| A | Disassembly interference matrix |
| $A_{ij}$ | Element of A and it represents the set of parts that interfere with part $v_i$ when $v_i$ is disassembled along *y* direction |
| *b* | Constant for interpreting the shape of logarithmic spiral |
| *C* | Contact-connection matrix |
| CA | Connector structures set |
| $CD_{ij}$ | Constant direction of part j to part i |
| $c_i$ | Assembly complexity |
| $c_{ij}$ | Contact and connection relationship |
| $C_j$ | Connector structure |
| *cmax* | Maximum time allowable in a workstation |
| *ct* | Cycle time |
| *D* | Assembly direction |
| $D_i$ | Distance of *i*-th moth |
| $D(S_k)$ | Set of detachable parts under $S_k$ |
| E | The set of edges of *G* |
| *EI* | Energy utilisation |
| *FA*(*P*i) | Feasible assembly sequence |
| *FA* (*P*i, *P*j) | Empty set |
| $F_j$ | *j*-th flame |
| $F(v_i\ (S_k))$ | Constraint degree of part *v*i $(S_k)$ |
| f1 | Sequence |
| *G* | Product assembly association graph |
| $H_0$ | Null hypothesis |
| $H_1$ | Alternate hypothesis |
| *I* | Initialisation function |
| L | Connection set of edges |
| *lb* | Lower bound |
| *m* | Assembly time |
| *M* | Number of moths |

| | |
|---|---|
| $M_i$ | $i$-th moth |
| $M(S\text{k})$ | Disassembly constraint matrix |
| *MW_matrix* | Moving wedge matrix |
| $n$ | Number of variables (dimension) |
| $N_{pw}$ | Amount of power consumption |
| *ntp* | Number of assembly parts |
| *ot* | Operation time |
| $P$ | Assembly power |
| *pt* | Processing time |
| $R(v_i)$ | Contact constraint set of part $v_\mathrm{i}$ |
| $r$ | Adaptive convergence constant |
| $s_i$ | Assembly stability |
| $S_k$ | Constraint status when the product is disassembled $k$ times |
| $T$ | Set of assembly tool |
| $t$ | Random number in $[-1, 1]$ |
| *ts* | Number of assembly tasks |
| *ub* | Upper bound |
| V | The set of nodes of $G$ |
| $v_{\text{base}}$ | Assembly base part |
| $W$ | Using matrix of assembly tool |
| $\pm x$ | X-axis direction |
| $\pm y$ | Y-axis direction |
| $\pm z$ | Z-axis direction |
| $\Omega$ | Parts set assembled before part $i$ |
| $\wedge$ | Logical operator |
| $\vee$ | Logical operator |

## LIST OF ABBREVIATIONS

| | |
|---|---|
| AC | Minimise Assembly Complexity |
| ACO | Ant Colony Optimisation |
| ALO | Ant Lion Optimiser |
| ANOVA | Analysis of Variance |
| AOTC | Minimise Assembly Operation Type |
| APL | Minimise Assembly Production Level |
| AS | Maximise Assembly Stability |
| ASP | Assembly Sequence Planning |
| ATTD | Minimise Assembly Tool Travel Distance |
| BPSO | Binary Particle Swarm Optimisation |
| C | Precedence Constraint |
| CAD | Computer Aided Design |
| CAS | Constraint Assembly State |
| CB | Connector-Based |
| CCM | Contact-Connection Matrix |
| CD | Constraint Direction |
| CPU | Central Processing Unit |
| CPSO | Chaotic Particle Swarm Optimisation |
| CS | Minimise Connector Similarity |
| CSAM | Connector Structure Assembly Model |
| CT | Minimise Cycle Time |
| DAG | Directed Acyclic Graph |
| DC | Direction Change |
| DFMA | Design for Manufacturing and Assembly |
| df | Degrees of Freedom |
| EE-ASP | Energy Efficient Assembly Sequence Planning |
| FA | Firefly Algorithm |
| FWA | Fireworks Algorithm |
| GA | Genetic Algorithm |
| GSA | Genetic Simulated Annealing |
| GWO | Grey Wolf Optimiser |

| | |
|---|---|
| IA | Immune Algorithm |
| LSD | Least Significant Difference |
| MA | Memetic Algorithm |
| MCAS | Minimal Constraint Assembly State |
| MFO | Moth-Flame Optimisation |
| MO | Multi-Objective |
| MS | Mean Square |
| MSW | Mean Square Within |
| NFL | No-Free-Lunch |
| NN | Neural Networks |
| NOW | Minimise Number of Workstations |
| NP | Non-Deterministic Polynomial-Time |
| OHM | Other Heuristic Methods |
| PB | Part-Based |
| PM | Precedence Matrix |
| PR | Precedence Relation |
| PSO | Particle Swarm Optimisation |
| SCA | Sine Cosine Algorithm |
| SO | Single Objective |
| SS | Sum of Degrees |
| SSA | Scatter Search Algorithm |
| TB | Task-Based |
| TC | Tool Change |
| TWO | The Whale Optimisation |
| Q&A | Question-and-Answer |
| WS | Workstation |

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