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Using Queuing Theory and Simulated Annealing to design the facility layout in an AGV-based modular manufacturing system

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Abstract

An automated guided vehicle-based flow production system is used for manufacturing prefabricated bathroom units. One unit can occupy a space of more than 10m². Due to large time deviations in sequential processes, queues are formed and greater plant space is needed. Reducing work-in-progress helps to save plant space but renders manufacture less efficient. The research explores better workstation arrangements. An open queuing network model was used to approximate the flow production system. Since the problem of workstation arrangement is a combinatorial optimisation problem, simulated annealing was applied to search for a good solution. The combination of an open queuing network model and simulated annealing provides a powerful tool to solve the facility layout problem for a stochastic flow production system. The experimental results show that the proposed approach has potential to guide industrial layout design and practice.

Keywords: facility layout, flow lines, queuing theory, modular manufacturing, simulated annealing

Graphical Abstract

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1. Introduction

The construction industry is increasingly transforming from predominantly on-site construction to greater off-site construction through prefabrication and delivery to the site for assembly and installation. Benefits of offsite prefabrication have been widely recognised through time savings, quality improvements, relieving skills shortages, cost reduction, and productivity improvement (Alazzaz & Whyte, 2014). Across the spectrum of off-site products, modular units are the most complete in terms of factory finishes. They can be transported, stacked on site and installed with efficient mechanical handling. The benefits of modularization have been claimed in the whole life cycle of buildings (Sonogo, et al., 2018). From 2014, the use of prefabricated bathroom units (PBU) has been mandated by the Building and Construction Authority (BCA) of Singapore for all non-landed residential government land sale (GLS) development sites (www.bca.gov.sg).

Prefabrication puts pressure on modular unit manufacturers to upgrade their production processes towards just-in-time (JIT) goals, as increasing demand for modular units (arising from the legislation in Singapore for example) have revealed the need for an efficient modular manufacturing system.

To address this need, a new concept of using automated guided vehicle (AGV)-based flow production systems for modular fabrication is proposed. In the proposed system, AGVs transport work-in-progress between different workstations in the manufacturing facility. Furthermore, implementing an AGV system facilitates the development of a computer integrated manufacturing (CIM) system approach which can control the entire production process (Lee & Leonard, 1991).

Productivity improvement is the key advantage of a flow production method over the more traditional fixed-position production method. While the fixed-position production method is used in large scale manufacturing such as that required for aircraft and ships, the flow production method is best suited to high volume manufacturing of a single product or product group (Murray, 2018).

In many modular factories, the workstations are arranged without meticulous planning (Banerjee, et al., 2006). However, the facility layout is a crucial element affecting the efficiency of a flow production system. A well-designed layout helps to maintain a consistent flow of units through the facility.

This study proposes a technique for use in the design of a facility layout in a modular manufacturing environment for PBUs. Given a number of workstations, their operational placements are to be determined.

In our proposal, the manufacturing system is represented in an open queuing network (OQN) model for ease of analysis. Due to the size of the PBUs, large storage space is needed as shortage of space can lead the system to deadlock. Since reduction of work-in-progress (WIP) helps to reduce the need of storage space, the manufacturing problem is then formulated into an optimisation model with the objective of minimizing WIP and solved using a simulated annealing (SA).

The paper is organized as follows: following this introduction is literature review. Then the AGV-based modular manufacturing system structure and its business process flow are shown in Section 3. The open queuing network model is described in Section 4. After that, Section 5 presents the optimisation model, and Section 6 explains the SA solving method. The case study is provided in Section 7, and the conclusions follow in Section 8.

2. Literature review

AGV systems are widely used in facilities such as manufacturing plants, warehouses, distribution centers and trans-shipment terminals where there are a large number of turnaround operations (Lee & Leonard, 1991). Employing efficient materials flow systems can result in a significant reduction in stocking requirements and ensure shorter cycle time in manufacture (Ulrich Piepel, 1989).

As the vehicles are programmable and operate without constant human intervention, their use enables easy alteration to production lines when production needs change (Egbelu & Roy, 1988).

The proposed AGV-based PBU manufacturing system is similar to an AGV-based flexible manufacturing system (AGV-FMS). The latter comprises a group of workstations integrated by automated material handling equipment and controlled by a central computer (Maughan & Lewis, 2000). AGV-FMS have drawn the attentions of many researchers (Vosniakos & Davies, 1988; Sabuncuoglu & Hommertzheim, 1992; Ulusoy, *et al.*, 1997; Reddy & Rao, 2006; Umar, *et al.*, 2015).

Facility layout is a crucial element to a flow production manufacturing system (Abu Hammad, *et al.*, 2008). Many industrial case studies have shown that simply applying AGV systems to conventional functional layouts may have caused more problems than benefits (Lee & Leonard, 1991). The problem of facility layout planning (FLP) has been actively studied for over six decades (Hosseini-Nasab, *et al.*, 2018). In the majority of reported FLP situations, materials handling costs are found to be the most important indicator to assess the effectiveness of a layout.

The problem is often formulated as a quadratic assignment problem (QAP) (Koopmans & Beckmann, 1957) and solved by different meta-heuristic approaches (Singh & Sharma, 2006). Simulated Annealing is one such meta-heuristic popularly used to solve FLP (Meller & Bozer, 1996; Chwif, *et al.*, 1998; Baykasoglyu & Gindy, 2001; Sahin & Türkbe, 2009).

QAP assumes all the departments in the facility are of equal area and calculates the centroid-to-centroid distances between the pairs of departments. Armour and Buffa (1994) proposed a modified QAP for an unequal-area facility layout problem by breaking the departments into small grids with equal area, assigning an artificial flow between those grids of the same department to ensure that they are not split, but this modified QAP is very difficult to solve due to the increase in the number of separate departments. Moreover, it has been shown that such an approach is ineffective because it implicitly imposes shape constraints on the departments (Bozer & Meller, 1997).

An alternative technique is Computerised Relative Allocation of Facilities Technique (CRAFT), which was first proposed by Armour and Buffa (1963). CRAFT uses a pairwise exchange to develop improvements over the existing layout. It requires an initial layout, cost and load matrix per unit distance, and distance matrix. Although CRAFT yields a good heuristic solution, it does not guarantee optimality because not all the combinations are evaluated.

The layout problem of FMS consists of machine layout which is in the context of detailed layout. The previous facility layout approaches that only generate block layouts are not appropriate for the layout problem of FMS (Tubaileh & Siam, 2017). As the workstations are arranged along the AGV travelling path, the corresponding layout problem is a single row layout problem (SRLP) (Keller & Buscher, 2015). SRLP is categorised as a more general FLP in that the block layout has to be detailed in the subsequent stage where machine layout problems are considered (Meller & Gau, 1996). The layout configurations of SRLP can be designed as straight line, semi-circular, U-shape and loop (Drira, *et al.*, 2007). It is often studied in the environment of cellular layout (Keller & Buscher, 2015). The existing cell formation (CF) problems comprise of three inter-related decisions: (1) identification of part families, (2) identification of machine cells, and (3) allocation of the families to cells or vice versa (Selim, *et al.*, 1998). Duplication of machines is often not allowed in the general CF models. However, this assumption is not appropriate for the PBU manufacturing problem presented in this paper.

With its lines and nodes structure, an SRLP can be easily transformed into a queuing network model. The queuing model enables the consideration of more realistic features of industrial systems such as the stochastic nature of the demand and the waiting phenomena induced by the unavailability of servers. It permits many operational performance factors including work-in-progress (WIP) and utilization to be quantified. However, a queuing model itself is not an optimizing model. To help decision makers to find a good layout solution, an optimisation algorithm is often combined with a queuing model. For example, Raman *et al.* (2009) combined a genetic algorithm (GA) with a queuing network model for a facility layout problem. GA converges fast at the beginning stage, but in the later stage it is likely to suffer a premature problem. Pourvaziri and Pierreval (2017) combined a cloud-based multi-objective simulated annealing approach with a queuing network model to solve the dynamic facility layout problem. The core of their model is still a QAP model.

Based on the existing technologies and theories, we propose an approach for the design of facility layout in a modular manufacturing environment for PBUs.

The PBU manufacturing system has several unique features. Firstly, there are great variations in the service time required at different workstations. For example, tiling units can take two days whereas water ponding test is only one hour. Secondly, inspections are required after each processing step. The interim products may then have to be temporarily removed from the manufacturing system in some critical inspection cases. Unit settling is needed following some operations such as tiling and ponding. Settling can take one or two days. Consequently, a large storage space is needed to accommodate the queues, the removed units and the settling needs of work-in-progress units.

In this regard, merely focusing on minimizing the manufacturing cycle alone will not result in a feasible production plan because the generated solution may require storage space beyond the capacity of the facility to provide; and the whole system is in danger of becoming deadlocked.

As WIP determines the need for space, the focus of the research proposed is placed on reducing WIP. So we deal with the facility allocation problem, i.e. given the workstation configuration, the performing operations are to be decided. The proposed approach will be unique. The PBU modular manufacturing system will be expressed in an OQN and operation assignment on the workstations will be optimised using SA.

3. System description

Modular units, such as PBUs comprise one of the more labour-intensive elements to be prefabricated. The manufacturing steps involving multi-disciplines (different trades) in activities in sub-components such as the structure, wall, floor, ceiling, door, waterproofing, finishes, sanitary fixtures and hardware, associated plumbing, ventilation and electrical works. The scope of this study is confined to the work relating to the 3D blocks.

Current prefabrication practice requires workers to look for their assigned PBUs which are placed in rows across the facility. They have to carry their equipment and tools to each unit and arrange for the required materials to be brought to the unit location. This requires complex logistics before any work on each unit commences.

The proposed system is an AGV-based flow system. The manufacturing process is thereby divided into many different operations and each operation is performed at a designated workstation. Thus the workers stay at their designated workstations while the work-in-progress PBUs are moved around the plant area using identical AGVs.

This proposal requires consideration of the necessary hardware structure for the system; and the corresponding business process.

3.1. Hardware structure

The concept proposes a wireless-based computer-integrated manufacturing (CIM) system. The system structure is shown in Figure 1. A master controller server which plans and controls the production lines communicates with a robot server which manages the AGV fleet using application programming interface (API) technology. Three kinds of graphical user interfaces (GUIs) are designed to cater for different user roles: worker, manager and inspector. Each PBU is placed on a flatbed table. AGVs then hoist and move the tables around the facility to the required workstations.

The AGVs used in the system are free-ranging, i.e., their preferred tracks are software programmed, which gives system flexibility to make adjustments when production changes are needed. On the floor, reflective papers, signs or panels are used to help the AGVs to determine their locations, and then move along the desired path.

Figure 1. Hardware system for the AGV-based modular manufacturing system.

3.2. Business process flowchart

Understanding the general business process is crucial to the design of a feasible facility layout. Figure 2 shows the business process flowchart for the proposed AGV-based modular fabrication system. Once workers at the fixed-position workstations receive the task alert, they will access the relevant operation manuals through touchscreen interfaces. Workers then confirm receipt of the necessary materials and update this information to the centralised database together with the actual operation start and finish times. If settling is needed after a workstation activity, an AGV will come and move the modular unit to the storage area. Inspections can be done either at the workstation during or after the operation, or in a specific inspection area after the settling in the storage area. If the inspecting time is expected to take a long time, the PBU will be moved to a designated inspection area by an AGV in order avoid interrupting the normal operations of the manufacturing system. When the unit passes the quality/inspection check, it will be returned to the system to receive its remaining operations, or otherwise be moved to the storage area to awaiting instructions for either rework or repair. Finished units are moved to a delivery area for loading onto the trucks and delivery to their respective construction sites.

Figure 2. Business process flowchart in the fabrication area.

Figure 3 shows a recommended plant layout pattern according to the proposed business process flowchart. The materials storage area is placed close to the workstations in order to minimize material handling time and cost. A large central area is proposed as a non-working zone for AGV parking. The Inspection and Delivery areas are placed near to the PBU storage area. The Proposed system lies inside the Workstation area. The Materials Storage area has easy access to the Workstation area.

Figure 3. Recommended plant layout pattern.

The proposed manufacturing system is a semi-automated system in that workers are at the workstations while computer-controlled vehicles travel between the workstations and the Inspection, Storage and Delivery areas. In this sense, the system is theoretically not an AGV-FMS as is not entirely automated. Robotic systems at the workstations would be required for full automation.

4. Queuing network model

Figure 4 illustrates an open queuing network model which approximates the PBU manufacturing system. The routes for every product type are pre-determined. In the model, queues are generated before operations begin at the workstations. Under equilibrium conditions, the average flow leaving the queue will equal the average flow entering the queue. The arrival rate at a workstation is influenced by the arrival rates of customer orders for PBUs and the throughput rates of other workstations. If the arrival pattern is Poisson distribution, then combining independent Poisson processes leads to a process which will also be Poisson in nature. This model includes multiple service centers and the multiple servers share one single queue. Therefore, using conventional notations, the queue model can be represented by $(M/M/c):(GD/\infty/\infty)$, indicating a queue system with the arrival pattern following the Poisson distribution, exponentially distributed service time, multiple servers, any type of priority rule, unlimited queue capacity and unlimited size of resource.

However, Poisson distribution is often used to describe the number of times an event occurs in a finite observation space. It is an appropriate model only if the following assumptions are true.

- (1) *Independence*: events must be independent.
- (2) *Homogeneity*: the rate at which events occur is constant.
- (3) Time period or space must be fixed.

The mean and variance of Poisson distribution are the same; both are λ . But in practice, the variance is usually larger than the theoretical variance and in the case of Poisson, larger than its mean. This is known as *over-dispersion*. Analyses assuming Poisson distribution are sometimes invalid because of the effect of over-dispersion. As the real manufacturing system is subject to random failure and other uncertainties, it is inevitable that the mean and variance will change. Therefore, the assumptions that are required for the Poisson distribution may be too conservative.

Figure 4. An example of a queuing network model for a modular manufacturing system with four workstation groups.

5. Optimisation model formulation

Formulation of the optimising model requires consideration of the main assumptions for the model and the underlying mathematical expressions.

5.1. Main assumptions

The main assumptions in formulating the model include:

- (1) The processing time, settling time, and inspection time for all operations of a PBU type at and after different workstations are known and deterministic regardless of the product type;
- (2) The arrival rates and service rates follow Poisson distributions;
- (3) The processing sequence for a PBU type is known and deterministic;
- (4) The demand for each PBU type is known and deterministic;
- (5) The planning horizon is given;
- (6) The service time of each individual PBU is composed of processing time on the workstations, settling time in the storage area, and inspection time in the inspection area. Inspection time on the workstation and AGV travelling time are not considered;
- (7) If the workstation is still busy processing with other PBUs, the PBU will queue in its current position in the storage area;
- (8) Workstation configuration is given;
- (9) Facility equipment can be ignored;
- (10) Sufficient AGVs are always available when required.

5.2. Mathematical optimisation model

The optimisation problem is formulated into a constraint programme. The output of this optimisation model is the optimal operation arrangement of the workstations.

5.2.1. Notations

Indices		
i :	PBU type	$1,2,3, \dots, I$
j, k :	workstation group type (operation type)	$1,2,3, \dots, J$
s_i	the first workstation group PBU i visits according to its processing sequence	$1,2,3, \dots, J$
Parameters		
C :	total number of available workstations	
PH :	planning horizon during which demand is to be met	
a_{js_i} :	1 if workstation group j is the first workstation group that PBU i visits; 0 otherwise	
λ_{ij} :	arrival rate of PBU i at workstation group j	
μ_j :	service rate of individual workstation in workstation group j	
τ_{ijk} :	arrival rate of PBU i at workstation group k from workstation group j	
P_{ijk} :	portion of PBU i leaving workstation group j for workstation group k	
ρ_j :	utilization of individual workstation in workstation group j	
D_i :	demand of PBU i	
PT_j :	mean processing time of PBUs at workstation group j	
ST_j :	mean settling time of PBUs at workstation group j	
IT_j :	mean inspecting time of PBUs at workstation group j	
WIP_j :	work-in-progress at workstation group j	
Q_j :	the number of PBUs waiting in queue for operation at workstation group j	
b_{ijk} :	processing route parameter, which is 1 if workstation group k is needed just after the workstation group j in the processing route of the PBU i ; and 0 otherwise	
Decision variables		
X_j :	workstation number at workstation group j	$1,2,3, \dots, C$

5.2.2. Objective function

This is a minimization optimisation model. The objective of the model is to minimise the work-in-progress (WIP) effects. According to the queuing theory, for queue model (M/M/c):(GD/ ∞/∞), the expected number of PBUs in queue is

$$Q_j = \frac{\rho_j^{X_j+1}}{(X_j-1)!(X_j-\rho_j)^2} \theta_j, \forall j \quad (1)$$

where

$$\theta_j = \left\{ \sum_{n=0}^{X_j-1} \frac{\rho_j^n}{n!} + \frac{\rho_j^{X_j}}{X_j!} \left(\frac{1}{1-(\rho_j/X_j)} \right) \right\}^{-1}, \forall j \quad (2)$$

The utilization ρ_j of workstation group j will be

$$\rho_j = \frac{\sum_i^I \lambda_{ij}}{\mu_j}, \forall j \quad (3)$$

λ_{ij} which is the arrival rate of PBU i at workstation group j can be calculated using Eq. (4). It is either from external customer order if this is the first workstation group of the PBU according to its processing sequence or from other workstation groups.

$$\lambda_{ij} = \alpha_{js_i} \times \frac{D_i}{PH} + (1 - \alpha_{js_i}) \times \sum_{k \neq j}^K b_{ikj} \times \tau_{ikj}, \forall i, j \quad (4)$$

where

$$\tau_{ikj} = P_{ikj} \times X_k \times \mu_k, \forall i, j, k \quad (5)$$

μ_k is the inverse of the service time which is given by

$$\mu_k = \frac{1}{PT_k + ST_k + IT_k}, \forall k \quad (6)$$

Then, according to the Little's Law, the work-in-progress in stable status is given by

$$WIP_j = Q_j + \rho_j, \forall j \quad (7)$$

5.2.3. Constraints

The total number of workstations assigned to the workstations groups should be equal to the total number of available workstations:

$$\sum_j^J X_j = C \quad (8)$$

To make the queuing network system develop a steady status, it is assumed $\sum_i^I \lambda_{ij} < X_j \times \mu_j, \forall j$. Otherwise, the queue will grow infinitely long. Then for every workstation group, there is a lower bound for the number of workstations, which is given by

$$X_j > \sum_i^I \left(\alpha_{js_i} \times \frac{D_i}{PH \times \mu_j} + (1 - \alpha_{js_i}) \times \sum_{k \neq j}^J b_{ikj} \times P_{ikj} \times X_k \times \frac{\mu_k}{\mu_j} \right), \forall j \quad (9)$$

In order to fulfill the assumption of a queuing model, the following scenario is created: there is a huge demand for standard PBU products since one construction project may need hundreds or even thousands of them and the prefabrication manufacturer may serve several construction projects simultaneously. The product release process should tally with onsite construction progress. Late delivery will be punished but earlier delivery is also not preferred since the modular products will have to occupy space on the construction site which may be constricted already. Consequently, the PBU release process should be controlled and delivery undertaken at a steady pace. As there are only a few key players in PBU manufacturing market, strong negotiation power on the part of the manufacturer's sales team is assumed. Therefore the sales team should be able to arrange for the lead time to mitigate the queue growth.

6. Simulated annealing approach

As the developed mathematical model is a complex integer programming model which is hard to solve, a simulated annealing (SA) approach is proposed. This section describes the parameters and approach.

6.1. Parameters

ΔE :	change in value in the objective function
ΔE_{max} :	the maximal value difference in the objective function between any two neighbouring solutions
T :	the global temperature
T_0 :	the initial temperature
T_f :	the termination temperature
K_b :	the Boltzmann constant having value 1.38×10^{-16} erg/K
P :	the transition acceptance ratio
P_0 :	the transition acceptance ratio at the initial stage
P_f :	the transition acceptance ratio at the ending stage
γ :	the declining rate
C :	the total number of temperature declining cycles

6.2. Approach

SA was first proposed by Kirkpatrick *et al.* (1983). It is a meta-heuristic technique able to provide a ‘good’ solution in a ‘reasonable’ amount of time regardless of the problem complexity. The method is motivated by an analogy to a physical phenomenon in crystallization, specifically to the way that metals cool and anneal. Successful applications of SA are witnessed in various problems including demand forecasting (Karadede, *et al.*, 2017), facility location (Wu, *et al.*, 2017) and location-routing (Yu & Lin, 2016).

Implementation of SA is surprisingly simple as it requires the selection of only one parameter: the number of iterations. Starting from an initial state, the system is perturbed at random to a new state in the neighbourhood of the original one. If the change results an improvement of objective function value (OFV), i.e. for a minimization problem, the OFV of the new solution is less than that of the previous solution, the transformation to the new state is accepted; otherwise the transformation is accepted with a temperature adaptive probability. The acceptance probability falls along with the temperature drops. In this way SA has the ability to escape from local optima and seek to find higher quality solutions. After running a certain number of iterations, the system eventually reaches an equilibrium.

To construct a simulated annealing, the following elements must be provided:

- *problem representation* that includes both a representation of the solution space and an appropriate and computable objective function measuring the quality of a given solution.
- *Transition mechanism between solutions* that slightly modify the current solution to move to the next state.
- *Cooling schedule* governs how a bad transition is accepted as a function of time that includes initial system temperature, temperature decrement function, number of iterations between temperature change, acceptance criteria and stop criteria.

The pseudo-code of the simulated annealing procedure is given as below:

Simulated annealing procedure
<ol style="list-style-type: none"> 1. Generate an initial solution at random and initialise T 2. While (thermal equilibrium not reached) do <ol style="list-style-type: none"> a. While (smaller than a constant number of iterations) do <ol style="list-style-type: none"> 1) Generate a neighbour state at random and evaluate ΔE.

<p>2) If $\Delta E < 0$, update the current state with the new state.</p> <p>If $\Delta E \geq 0$, update the current state with the new state with the probability $P = \frac{-\Delta E}{K_b \cdot T}$,</p> <p>b. Decrease T according to the annealing schedule.</p> <p>3. Output the solution having the lowest OFV.</p>
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To use a simulated annealing, one has first to define the solution space. Since the workstations are merely platforms for performing manual work, they are completely flexible to all operations. The problem is designed as an ‘assignment’ problem in that each workstation is given an operation and performs that operation throughout the production period. This gives the ideal case since frequent changes on operations will eventually extend the production time. Consequently, the proposed solution is represented by a series of integer digits. Each digit points to a workstation group, i.e., a type of operation, and the digit itself indicates the number of workstations required in that workstation group, i.e., to perform that type of operation. For example, 17 14 26 12 7 represents that 17 workstations in workstation group 1, 14 workstations in workstation group 2, and so on.

A new solution is generated by swapping a random number of workstations in the current solution. Compared to GA, the procedure of generating new solution using SA is more controllable. This step is repeated for a certain number of times: *NOVER*; or until the number of new solutions accepted exceeds a given number: *NLIMIT*. Every newly-generated solution should be checked for its feasibility in terms of the constraints. Only the surviving solutions are evaluated for their qualities. In order to increase the survival probability of the initial solution and to save computational costs, the following heuristic is used to create it.

Heuristic for creation of the initial solution
<ol style="list-style-type: none"> 1. Assign each workstation group one workstation. 2. Calculate the required minimum number of workstations for each workstation group. 3. For each workstation group, while (number of workstations is smaller than the minimum value) do <ol style="list-style-type: none"> a. Assign workstations to this group until satisfying the minimum requirement. b. Update the minimum number of workstations c. Break the iteration when all the workstations have been assigned. 4. Assign the remaining workstations to randomly selected workstation groups.

The initial temperature must be ‘hot’ enough to accept almost all changes from the initial state. At the same time, it should not be so hot that it makes random searching time too long. Many methods have been proposed to compute the initial temperature (Ben-Ameur, 2004). They are summarised below:

- (1) $T_0 = \Delta E_{max}$
- (2) $T_0 = K \cdot \sigma_{\alpha}^2$, where K is a constant ranging from 5 to 10 and σ_{α}^2 is the second moment of the energy distribution when the temperature is α
- (3) compute a temperature such that the transition acceptance ratio is approximately equal to a given value P_0

The third method is adopted for the proposed SA. The initial temperature is computed using the formula:

$$T_0 = -\frac{\Delta E_{max}}{K_b \ln(P_0)} \quad (10)$$

The temperature is then reduced following a designed cooling schedule. There are also many ways to construct the cooling schedule. These are summarised below:

- (1) arithmetic function $T_{i+1} = T_i - K$

- (2) geometric function $T_{i+1} = \gamma \cdot T_i$
- (3) Logarithmic function $T_{i+1} = K/(\log T_i)$
- (4) inverse function $T_{i+1} = K/(1 + T_i)$

where K, γ are constants, $i = 0, 1, \dots, C$.

Among these cooling schedules, the use of geometric function is the most common and it is used in the proposed SA. Generally, the temperature is decreased until it reaches zero. However, this can take a long time. Therefore different stopping criteria are used to terminate SA earlier. These criteria are summarised as below:

- (1) after a certain number of iterations having been executed
- (2) reach a given final temperature
- (3) no improvement in objective function value for a definite number of iterations
- (4) reach a defined probability of accepting a worse state

In the proposed SA, the fourth method is adopted. Then the termination temperature T_f is decided by P_f , which should be a very low number, for example, $P_f = 1 \times 10^{-15}$. When P_0, P_f and γ are all known, then the total number of temperature declining cycles can be derived from the formula:

$$\gamma = \sqrt[C]{(\log P_0)/(\log P_f)} \quad (11)$$

And T_f is calculated using the formula:

$$T_f = \gamma^C \cdot T_0 \quad (12)$$

Given this approach for the proposed model, a case study is presented.

7. Case study

The simulated annealing is programmed in C#, using a personal computer with 8 GB RAM and 2.10 GHz processor. A small-scale test case and a full-scale test case are used to show the performance of the developed approach.

7.1. Small-scale test case

7.1.1. Background

Firstly, an experimental small-scale case is used to verify the developed approach. The inputs to the queuing network model include processing routings, mean processing time, mean settling time, mean inspecting time, production volumes, planning horizon, number of workstations, and minimum number of operations. This information must be known. Table 1 gives the operation details for the small-scale test case. There are four elementary operations: ceiling frame, plumbing + electrical installation, tiling, and sanitary fitting + shower screen fixing. Table 2 provides the demands and the processing sequences of the different operations.

Table 1. Operation details for the small-scale test case.

Item	Operation	Time (hours)
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		Processing	Settling
P1	Ceiling Frame	3	0
P2	Plumbing + Electrical	6	0
P3	Tiling	24	12
P4	Sanitary fitting + shower screen	7	3

Table 2. Product volumes and processing sequences.

Product code	Quantity	Processing sequence
M01	15	P1→P2→P3→P4
M02	20	P1→P2→P3→P4
M03	85	P1→P2→P3→P4
T01	121	P2→P3→P4
T02	6	P1→P3→P4
T03	88	P1→P2→P3→P4

7.1.2. Analysis

According to Eq. (6), the service rates of workstation of each operation are:

$$\mu_1 = \frac{1}{3} \approx 0.3333, \mu_2 = \frac{1}{6} \approx 0.1667, \mu_3 = \frac{1}{36} \approx 0.0278, \mu_4 = \frac{1}{10} = 0.1$$

From Eq. (4), the arrival rates at each workstation group are:

$$\lambda_1 = \frac{15 + 20 + 85 + 6 + 88}{PH} = \frac{214}{PH}$$

$$\lambda_2 = \frac{121}{PH} + \frac{15 + 20 + 85 + 88}{15 + 20 + 85 + 6 + 88} \times 0.3333 \times N_1 = \frac{121}{PH} + 0.324 \times N_1$$

$$\begin{aligned} \lambda_3 &= \frac{6}{15 + 20 + 85 + 6 + 88} \times 0.3333 \times N_1 + 0.1667 \times N_2 \\ &= 0.009 \times N_1 + 0.1667 \times N_2 \end{aligned}$$

$$\lambda_4 = 0.0278 \times N_3$$

Then, the utilizations of each workstation group from Eq. (3) are:

$$\rho_1 = \frac{214}{0.3333 \times PH} = \frac{642}{PH}$$

$$\rho_2 = \frac{121}{0.1667 \times PH} + \frac{0.324}{0.1667} \times N_1 = \frac{726}{PH} + 1.9436 \times N_1$$

$$\rho_3 = \frac{0.009}{0.0278} \times N_1 + \frac{0.1667}{0.0278} \times N_2 = 0.3237 \times N_1 + 5.9964 \times N_2$$

$$\rho_4 = \frac{0.0278}{0.1} \times N_3 = 0.278 \times N_3$$

Using Eq. (9), i.e. the steady constraint, the lower bounds of the number of workstations in each workstation group can be obtained. The minimum required number of workstations has an inverse relationship with the planning horizon, that is, the shorter the planning horizon is given, and the more workstations are required. Theoretically there is no upper bound for the number of workstations. Table 3 provides the minimum number of workstations according to the given planning horizon. From Table 3, one can see that a stable number can finally emerges when the planning horizon is wide enough. The solution indicates that at least 20 workstations are needed for achieving a steady state. In an 8-hour day, a planning horizon of 20000 hours is equivalent to 2500 days. This amount of time is not realistic for a normal prefabrication project. For practical use, a narrower planning horizon is more meaningful. For example, it is reasonable to choose a planning horizon of 800 hours, which is equivalent to 100 days for a project. The result suggests the factory should therefore prepare 29 workstations. Assuming each workstation occupies a space of 16m² (4m x 4m), it then requires a reservation of 464 square meters for workstations in the manufacturing facility.

Table 3. Minimum number of workstations according to the planning horizon.

Minimum number of workstations for each operation	Planning horizon <i>PH</i> (hours)									
	100	200	300	500	800	1000	5000	10000	20000	∞
P ₁	7	4	3	2	1	1	1	1	1	1
P ₂	21	12	9	6	3	3	3	3	2	2
P ₃	129	74	55	37	19	19	19	19	13	13
P ₄	36	21	16	11	6	6	6	6	4	4
Total	193	111	83	56	29	29	29	29	20	20

Since the small-scale test case confirms the feasibility of the modeling approach, it is now possible to proceed to a full scale test.

7.2. Full-scale test case

7.2.1. Background

Data from a real industrial production project are used to demonstrate the performance of the developed approach. The selected case is a Singapore-based precast concrete PBU facility for a Housing and Development Board (HDB) apartment building project in Singapore. In order to boost construction productivity in Singapore, by 2019 all newly launched HDB apartment building projects must be fitted with bathroom units prefabricated and preassembled off-site. Figure 5 shows a sample precast concrete PBU.

Figure 5. Typical PBU for HDB housing projects.

In such projects, there are typically six types of PBUs. Their dimensions and requirements are described in Table 4.

Table 4. PBU properties for the full-scale test case.

Product code	Category	Name	Weight (mm)	Length (mm)	Width (mm)	Height (mm)	Demand
PBU-M01	Concrete	Master	6,350	2,743	1,828	3,048	31
PBU-M02	Concrete	Master	6,350	2,743	1,828	3,048	45
PBU-M03	Concrete	Master	6,350	2,743	1,828	3,048	180
PBU-T01	Concrete	Common	4,117	2,133	1,524	3,048	275
PBU-T02	Concrete	Common	4,117	2,133	1,524	3,048	12
PBU-T03	Concrete	Common	4,117	2,133	1,524	3,048	186

Table 5 gives the common processing sequence for a PBU.

Table 5. The processing sequences for the full-scale test case.

Sequence	Operation	Time (hours)	
		Processing	Settling
1	Ponding 1	1	24
2	Ceiling Frame	6	0
3	Waterproofing	24	0
4	Plumbing	6	0
5	Electrical	6	0
6	Tiling	48	24
7	Sanitary fitting	8	0
8	Shower screen	6	12
9	Spray test	4	0
10	Ponding 2	1	24
11	Packing	4	0

It can be seen that production flow backtracks to the operation of water ponding test after the operation of spray test. Moreover, settling is required after ponding, tiling and shower screen installations. Time in the inspection area is assumed to be 2 hours. Maintaining a high level of unit quality is very important since inspection failures leading to re-work can disturb the normal production flow in this manufacturing system.

Table 5 shows that there are large variations in the workstation service times among the different operations. Thus, in order to balance the queues in front of the workstation groups, one may want to group some workstations performing different operations as one 'composite workstation cell'. There could be many ways to group the sequential operations. But grouping priority should be given to those which do not require settling time afterwards. In order to further kill or diminish the queues, multiple identical workstations are allowed in one 'composite workstation cell'. With this in train, PBUs can go through all the processes within the cell with no need to go to storage area for settling or queuing. For example, the cell of the operations for ceiling frame, waterproofing, plumbing and electrical installations is shown in Figure 6.

Figure 6. Proposed composite workstation cells.

For a sub-optimal case, the operations with settling needs can also be allowed to be grouped in the ‘composite workstation cell’. For example, the cell of sanitary fitting, shower screen and spray test as shown in Figure 6 can be arranged in this way.

After settling in the storage area, the PBUs will return to the cell again. Table 6 gives the proposed workstation groups. Tiling is observed as the bottleneck. The amount of time required for tiling task could be reduced if robots are introduced.

Table 6. Proposed workstation groups for the full-scale test case.

Item	Operation	Service time* (hours)	Service rate
1	Ponding	27	0.037
2	Ceiling frame + waterproofing + plumbing + Electrical	42	0.0238
3		74	0.0135
4	Sanitary fitting + shower screen + spray test	32	0.0313
5	Packing	4	0.25

*The service time includes workstation processing time, settling time and inspecting time.

Finally, Figure 7 illustrates the corresponding queueing network model.

Figure 7. Queueing network model for the full-scale case.

7.2.2. Results

The SA parameter setting that is used for the case is as shown in Table 7.

Table 7. Parameter setting for SA.

Initial acceptance probability P_0 :	0.95
Terminating acceptance probability P_f :	1×10^{-15}
Declining rate in the cooling schedule γ :	0.98
NOVER:	$200 \times C$
NLIMIT:	$50 \times C$

Table 8 presents the optimal workstation arrangements, the utilisations of each workstation and the corresponding WIPs. Five planning horizons are studied: 2000 hours, 3000 hours, 4000 hours, 5000 hours and 10000 hours.

Table 8. Workstation arrangements, utilization and WIPs.

Total workstation Number	Operation 1		Operation 2		Operation 3		Operation 4		Operation 5		WIP
	n ^a	% ^b	n	%	n	%	n	%	n	%	
PH = 2000 hours											
88	22	98	18	95	32	99	14	99	2	81	363.78
89	22	98	18	95	32	99	14	99	3	54	360.85
90	22	98	18	95	32	99	14	99	4	41	360.48
91	23	98	18	99	33	96	15	95	2	85	339.10
92	23	98	18	99	33	96	15	95	3	57	334.95
93	23	98	19	94	34	98	15	98	2	85	265.54
94	23	98	19	94	34	98	15	98	3	57	261.39
95	24	97	19	98	34	98	16	92	2	89	261.90
96	24	97	19	98	35	96	16	95	2	89	226.57
97	24	97	19	98	35	96	16	95	3	59	220.32
PH = 3000 hours											
63	15	100	12	97	22	96	10	95	4	28	10132.88
64	16	94	13	96	23	100	10	99	2	59	520.33
65	16	99	13	96	23	100	11	90	2	59	432.10
66	16	99	13	96	24	95	11	94	2	59	220.21
67	16	99	13	96	24	95	11	94	3	40	219.60
68	16	99	13	96	24	95	11	94	4	30	219.47
69	16	99	13	96	24	95	11	94	5	24	219.42
70	17	98	14	94	25	99	12	90	2	63	217.13
71	17	98	14	94	26	95	12	94	2	63	167.83
72	17	98	14	94	26	95	12	94	3	42	167.07
PH = 4000 hours											
44	11	98	9	95	16	99	7	99	1	81	320.81
45	11	98	9	95	16	99	7	99	2	41	317.51
46	11	98	9	95	16	99	7	99	3	27	317.33
47	11	98	9	95	16	99	7	99	4	20	317.28
48	11	98	9	95	16	99	7	99	5	16	317.26
49	12	97	10	93	18	98	8	97	1	89	182.25
50	12	97	10	93	18	98	8	97	2	44	175.49
51	12	97	10	93	18	98	8	97	3	30	175.26
52	12	97	10	93	18	98	8	97	4	22	175.20
53	12	97	10	93	18	98	8	97	5	18	175.17
PH = 5000 hours											
41	10	98	8	94	15	94	7	93	1	74	163.08
42	10	98	8	97	15	94	7	93	2	37	161.18
43	10	98	8	97	15	94	7	93	3	25	161.05
44	10	98	8	97	15	94	7	93	4	19	161.01
45	10	98	8	97	15	94	7	93	5	15	160.99

46	11	97	9	95	17	93	8	92	1	81	121.63
47	11	98	9	97	17	93	8	92	2	41	118.33
48	11	97	9	95	17	93	8	92	3	27	118.15
49	11	97	9	95	17	93	8	92	4	20	118.10
50	11	97	9	95	17	93	8	92	5	16	118.08
PH = 10000 hours											
25	6	89	5	93	9	98	4	97	1	44	124.12
26	6	89	5	93	9	98	4	97	2	22	123.83
27	6	89	5	93	9	98	4	97	3	15	123.79
28	6	89	5	93	9	98	4	97	4	11	123.78
29	6	89	5	93	9	98	4	97	5	9	123.78
30	7	88	6	91	11	96	5	95	1	52	85.97
31	7	88	6	91	11	96	5	95	2	26	85.50
32	7	88	6	91	11	96	5	95	3	17	85.44
33	7	88	6	91	11	96	5	95	4	13	85.43
34	7	88	6	91	11	96	5	95	5	10	85.42

^a Number of workstations per group

^b Utilisation of workstation per group

Normally, the desired time for a production volume of 729 PBUs is between 1 and 2 years. Therefore, an optimal plan should be selected among those solutions when the planning horizons are less than 5000 hours. It is noticed from Table 8 that there are sudden drops of WIPs when there is only one workstation increase. For example, in the case where PH = 2000 hours, WIP can be dropped from 335 PBUs to 266 PBUs when the workstation number is increased from 92 to 93. Similarly, in the case where PH = 3000 hours, WIP can be dropped from 433 PBUs to 221 PBUs when the workstation number is increased from 65 to 66. In the case where PH = 4000 hours, WIP can be dropped from 318 PBUs to 183 PBUs when the workstation number is increased from 48 to 49. Where PH = 5000 hours, WIP can be dropped from 161 PBUs to 122 PBUs when the workstation number is increased from 45 to 46. We recommend selecting the workstation number near these transitions. For example, selections of 93 workstations, 66 workstations, 49 workstations and 46 workstations are all considered good according to different production times that the manufacturer is targeting. The corresponding WIP will be 266, 221, 183 and 122 respectively. Knowing one workstation occupies about 16m², and one PBU slot in the storage area requires about 10m² square meters, it is simple to work out the required space for the whole facility. However, a final design decision about the facility plan is influenced by many factors including forecasts of demand, the targeted lead time, available industrial land and premises, availability of suitably skilled workers, and availability of finance.

7.3. Further discussion

The best arrangement of workstations is eventually determined by trade-offs between the physical resource constraints of the factory and the time constraints associated with customer orders. Trial and error techniques are often applied during the course of trade-off selection. The corresponding deduced work-in-progress implies the capacity of the manufacturing system to absorb it.

The current solution indicates a fixed operation for one workstation. However, due to the unbalanced production line, the utilisations of some workstations are seen to be much lower than the others in the system. To counter this, it might be desirable to assign additional operations to those workstations in order to increase their usage. In fact, allowing re-arrangement of operations on the workstations during production can help to reduce space requirements, increase utilisation and better balance the production line. Simulation can help to explore and display these benefits.

The proposed queuing system assumes Poisson distribution which may be too conservative. Because of this, we recommend that management should set strict standard operating procedures for every operation in order to maintain a high level of production quality and avoid failures and the uncertainties that they bring.

In the proposed system, material handling costs are not explored. However, material handling cost can be critical when the fabrication facility becomes extensive or is carried out on multiple floor levels. The concept of multi-level fabrication is favored by land-scarce and land-expensive countries like Singapore. In a multi-level manufacturing situation, cellular design will display advantages. Cellular design is a lean manufacturing concept whereby workstations are arranged in sequences that support a smooth flow of materials and components with minimal transport or delay. The creation of composite workstation cells in the Singapore case study demonstrates the implementation of cellular design. Workstations in one cell could be placed on the same floor level. Storage areas may be allocated on several floor levels similar to a multi-level car park system. The PBUs would then be lifted to the various levels by gantries traversing openings in the floors. Vertical separation in this way could also benefit quality assurance as 'dirty' operations could be separated from those that are 'clean'.

8. Conclusions

An AGV-based modular manufacturing system is still a conceptual idea for the construction industry. However, the successful applications of AGV-based systems in other manufacturing industries such as automotive and electronic and white goods appliance manufacturing encourage its use in heavier industries.

We have proposed and explored a technique for use in the design of a facility layout in terms of workstation arrangement in an AGV-based manufacturing environment. In the proposed system, workers stay at their workstations and AGVs are used to move the PBUs progressively around the fabrication facility. The biggest advantage of this kind of flow production method over traditional fixed position production method is increased productivity. It may also improve safety since workers remain in areas that they know and are confident will be safe.

Nevertheless, a flow production method may require a larger fabrication area. Restrictions on space may cause a system to deadlock. Therefore, minimization of WIP is the main objective for the system.

The proposed AGV-based manufacturing system is approximated by an open queuing network model for ease of analysis. A constraint programming approach is developed and simulated annealing is implemented to solve the optimisation model. The best arrangement for workstations for a given production volume to be completed in a targeted time is selected by trial and errors. A small-scale test case and a full-scale test case are used to demonstrate the applicability and practicability of the developed technique. The results show that it is efficient and powerful.

Although the queuing model is a straightforward analytical model for the investigated problem, it has some drawbacks. Most importantly, the adoption of Poisson distribution poses some limitations on the analytical model. Over-dispersion in the real data can be a significant problem which could invalidate model. Models with random distributions should therefore be investigated in future research. The current model assigns one operation to one workstation. However, due to the imbalance in processing time, some workstations may have very low utilisations and thus the assignment of additional operations to workstations should be investigated. Further research could also explore the design of an optimised schedule for re-arrangement of the operations on the workstations.

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References

- Abu Hammad, A., Salem, O., Hastak, M. & Syal, M., 2008. Decision support system for manufacturing housing facility layout. *Journal of Architectural Engineering*, 14(2), pp. 36-46.
- Alazzaz, F. & Whyte, A., 2014. Uptake of off-site construction: benefits and future application. *International Journal of Civil and Environmental Engineering*, 8(12).
- Armour, G. C. & Buffa, E. S., 1963. A heuristic algorithm and simulation approach to relative location of facilities. *Management Science*, 9(2), pp. 294-309.
- Armour, G. C. & Buffa, E. S., 1994. *Heuristic algorithm and simulation approach to relative location of facilities*. Chicago, American Society of Mechanical Engineers, Materials Handling Division, MHD, pp. 101-116.
- Banerjee, D., Syal, M. & Hastak, M., 2006. Material flow-based facility layout analysis of a manufactured housing production plant. *Journal of Architectural Engineering*, 12(4), pp. 196-206.
- Baykasoglylu, A. & Gindy, N. N. Z., 2001. A simulated annealing algorithm for dynamic layout problem. *Computers & Operations Research*, Volume 28, pp. 1403-1426.
- Ben-Ameur, W., 2004. Computing the initial temperature of simulated annealing. *Computational Optimization and Applications*, Volume 29, pp. 369-385.
- Bozer, Y. A. & Meller, R. D., 1997. A reexamination of the distance-based facility layout problem. *IIE Transactions*, 29(7), pp. 549-560.
- Chwif, L., Pereira Barretto, M. R. & Moscato, L. A., 1998. A solution to the facility layout problem using simulated annealing. *Computers in Industry*, Volume 36, pp. 125-132.
- Drira, A., Pierreval, H. & Hajri-Gabouj, S., 2007. Facility layout problems: A survey. *Annual Reviews in Control*, Volume 31, pp. 255-267.
- Egbelu, P. J. & Roy, N., 1988. Material flow control in AGV/unit load based production lines. *International Journal of Production Research*, 26(1), pp. 81-94.
- Hosseini-Nasab, H., Fereidouni, S., Ghomi, S. M. T. F. & Fakhrazad, M. B., 2018. Classification of facility layout problems: a review study. *International Journal of Advanced Manufacturing Technology*, Volume 94, pp. 957-977.
- Karadede, Y., Ozdemir, G. & Aydemir, E., 2017. Breeder hybrid algorithm approach for natural gas demand forecasting model. *Energy*, Volume 141, pp. 1269-1284.
- Keller, B. & Buscher, U., 2015. Single row layout models. *European Journal of Operational Research*, Volume 245, pp. 629-644.
- Kirkpatrick, S., Gelatt, C. D. & Vecchi, M. P., 1983. Optimization by simulated annealing. *Science, New Series*, 220(4598), pp. 671-680.
- Koopmans, T. C. & Beckmann, M., 1957. Assignment problems and the location of economic activities. *Econometrica*, 25(1), pp. 53-76.
- Lee, R. J. V. & Leonard, R., 1991. The company-wide effects of just-in-time manufacturing within an integrated materials handling system: a case study. *Production Planning & Control*, 2(4), pp. 364-372.
- Lee, R. J. V. & Leonard, R., 1991. The role of automated guided vehicles within cellular manufacturing as a shop floor contribution to CIM. *International Journal of Computer Integrated Manufacturing*, 4(3), pp. 176-187.
- Maughan, F. G. & Lewis, H. J., 2000. AGV controlled FMS. *International Journal of Production Research*, 38(17), pp. 4445-4453.

- Meller, R. D. & Bozer, Y. A., 1996. A new simulated annealing algorithm for the facility layout problem. *International Journal of Production Research*, 34(6), pp. 1675-1692.
- Meller, R. D. & Gau, K. Y., 1996. The facility layout problem: recent and emerging trends and perspectives. *Journal of Manufacturing Systems*, 15(5), pp. 351-366.
- Murray, M., 2018. *Manufacturing process*. [Online]
Available at: <https://www.thebalance.com/manufacturing-process-2221376>
[Accessed 11 06 2018].
- Pourvaziri, H. & Pierreval, H., 2017. Dynamic facility layout problem based on open queuing network theory. *European Journal of Operational Research*, Volume 259, pp. 538-553.
- Raman, D., Nagalingam, S. V. & Gurd, B. W., 2009. A genetic algorithm and queuing theory based methodology for facilities layout problem. *International Journal of Production Research*, 47(20), pp. 5611-5635.
- Reddy, B. S. P. & Rao, C. S. P., 2006. A hybrid multi-objective GA for simultaneous scheduling of machines and AGVs in FMS. *International Journal of Advanced Manufacturing Technology*, Volume 31, pp. 602-613.
- Sabuncuoglu, I. & Hommertzheim, D. L., 1992. Dynamic dispatching algorithm for scheduling machines and automated guided vehicles in a flexible manufacturing system. *International Journal of Production Research*, 30(5), pp. 1059-1079.
- Sahin, R. & Türkbey, O., 2009. A simulated annealing algorithm to find approximate Pareto optimal solutions for the multi-objective facility layout problem. *International Journal of Advanced Manufacturing Technology*, Volume 41, pp. 1003-1018.
- Selim, H. M., Askin, R. G. & Vakharia, A. J., 1998. Cell formation in group technology: review, evaluation and directions for future research. *Computers & Industrial Engineering*, 34(1), pp. 3-20.
- Singh, S. P. & Sharma, R. R. K., 2006. A review of different approaches to the facility layout problems. *International Journal of Advanced Manufacturing Technology*, Volume 30, pp. 425-433.
- Sonego, M., Echeveste, M. E. S. & Debarba, H. G., 2018. The role of modularity in sustainable design: A systematic review. *Journal of Cleaner Production*, Volume 176, pp. 196-209.
- Tubaileh, A. & Siam, J., 2017. Single and multi-row layout design for flexible manufacturing systems. *International Journal of Computer Integrated Manufacturing*, 30(12), pp. 1316-1330.
- Ulrich Piepel, D.-I., 1989. Mobile robots into the next century. *Industrial Robot: An International Journal*, 16(4), pp. 216-220.
- Ulusoy, G., Sivrikaya-Serifoglu, F. & Bilge, U., 1997. A genetic algorithm approach to the simultaneous scheduling of machines and automated guided vehicles. *Computers & Operations Research*, 24(4), pp. 335-351.
- Umar, U. A., Ariffin, M. K. A., Ismail, N. & Tang, S. H., 2015. Hybrid multiobjective genetic algorithms for integrated dynamic scheduling and routing of jobs and automated-guided vehicle (AGV) in flexible manufacturing systems (FMS) environment. *International Journal of Advanced Manufacturing Technology*, Volume 81, pp. 2123-2141.
- Vosniakos, G. C. & Davies, B. J., 1988. Simulation study of an AGV system in an FMS environment. *The International Journal of Advanced Manufacturing Technology*, 3(4), pp. 33-46.
- Wu, T. et al., 2017. Lagrangean relaxation and hybrid simulated annealing tabu search procedure for a two-echelon capacitated facility location problem with plant size selection. *International Journal of Production Research*, 55(9), pp. 2540-2555.
- Yu, V. F. & Lin, S.-Y., 2016. Solving the location-routing problem with simultaneous pickup and delivery by simulated annealing. *International Journal of Production Research*, 54(2), pp. 526-549.