

Formulating and solving sustainable stochastic dynamic facility layout problem: a key to sustainable operations

Akash Tayal¹ · Angappa Gunasekaran² · Surya Prakash Singh³ · Rameshwar Dubey⁴ · Thanos Papadopoulos⁵

Published online: 21 October 2016
© Springer Science+Business Media New York 2016

Abstract Facility layout design, a NP hard problem, is associated with the arrangement of facilities in a manufacturing shop floor, which impacts the performance, and cost of system. Efficient design of facility layout is a key to the sustainable operations in a manufacturing shop floor. An efficient layout design not only optimizes the cost and energy due to proficient handling but also increase flexibility and easy accessibility. Traditionally, it is solved using meta-heuristic techniques. But these algorithmic or procedural methodologies do not generate effective and efficient layout design from sustainable point of view, where design should consider multiple criteria such as demand fluctuations, material handling cost, accessibility, maintenance, waste and more. In this paper, to capture the sustainability in the layout design these parameters are considered, and a new sustainable stochastic dynamic facility layout problem (SDFLP) is formulated and solved. SDFLP is optimized for material handling cost and rearrangement cost using various meta-heuristic techniques. The pool of layouts thus generated are then analyzed by data envelopment analysis to identify efficient layouts. A novel hierarchical methodology of consensus ranking of layouts is proposed which combines

✉ Angappa Gunasekaran
agunasekaran@umassd.edu

Akash Tayal
akashtayal@yahoo.com

Surya Prakash Singh
surya.singh@gmail.com

Rameshwar Dubey
rameshwardubey@gmail.com

Thanos Papadopoulos
A.Papadopoulos@kent.ac.uk

¹ Indira Gandhi Delhi Technical University for Women, Delhi, India

² Charlton College of Business, University of Massachusetts, Dartmouth, MA, USA

³ Department of Management Studies, Indian Institute of Technology Delhi, Delhi, India

⁴ Symbiosis Institute University, Pune, India

⁵ Kent Business School, University of Kent, Canterbury, UK

the multiple attributes/criteria. Multi attribute decision-making techniques such as technique for order preference by similarity to ideal solution, interpretive ranking process and analytic hierarchy process, Borda–Kendall and integer linear programming based rank aggregation techniques are applied. To validate the proposed methodology data sets for facility size $N = 12$ for time period $T = 5$ having Gaussian demand are considered.

Keywords Stochastic dynamic facility layout · Simulated annealing · Chaotic simulated annealing · TOPSIS · AHP · DEA · Borda–Kendall · Flow distance · Accessibility · Maintenance · Sustainable operations

1 Introduction

In recent years, sustainable operations management has attracted attention from both academics and practitioners. The concept of ‘sustainable operations management’ has gained serious considerations due to scarce natural resources and rapid change in climate and increasing social inequality, which forced enterprises to revisit their operations management practices to address 3Ps, that is, planet, people, and profit (Drake and Spinler 2013). Since the 1980s Kleindorfer and Kunreuther (1994) have argued how operations management practices can contribute towards sustainability. Since then, over three decades, work on sustainable operations is still in its infancy. The sustainable operations management field has been rapidly replaced by the holistic term “sustainable supply chain management (SSCM)” (see Govindan and Cheng 2015). Still, sustainable operations decisions and in particular facility layout are important and need to be guided by low cost and environmental related regulatory norms (Bayraktar et al. 2007; Subramoniam et al. 2009).

In this paper we are concerned with facility layout decision in sustainable operations. In recent years it has been noted that most of the manufacturing units have been moved to low labor cost country and weak regulatory norms. There is a rich body of literature on facility layout problems that focuses on cost, but research on facility layout design from a sustainability point of view is scant (Sacaluga and Frojan 2014). Hence, we argue that to offer holistic solutions to current problems, the 3 pillars of sustainability—economic, social and environment must be aligned in finding a desirable facility layout which is shown in Fig. 1.

A typical facility layout problem involves optimum placement of facilities by minimizing the material handling cost. However, due to fluctuation in economic and political situations and seasonal changes the production rates inevitably fluctuate. A stochastic dynamic facility layout model incorporates these variations as an expression of demand variability in the facility layout. These are expressed as probability distribution function. This argument is formulated as a mathematical expression with the aim to minimize the material handling and rearrangement cost (quantitative factors) and is known as stochastic dynamic facility layout problem (SDFLP). This model, however, ignores social and environmental factors such as ease of maintenance, waste disposal, ease of working, and job creation. These characteristics can be expressed as qualitative parameters, and when associated with the SDFLP model provides a sustainable SDFLP model, which can be solved to get a sustainable layout. The framework of proposed sustainable SDFLP is shown in Fig. 2.

In the paper, a novel method is proposed which solves sustainable SDFLP considering both qualitative and quantitative factors under stochastic product demand flow over multi time period, using the hierarchical framework of-meta heuristic, multiple attribute decision making (MADM) techniques and consensus ranking method. The proposed methodology

Fig. 1 3-Ps of sustainability

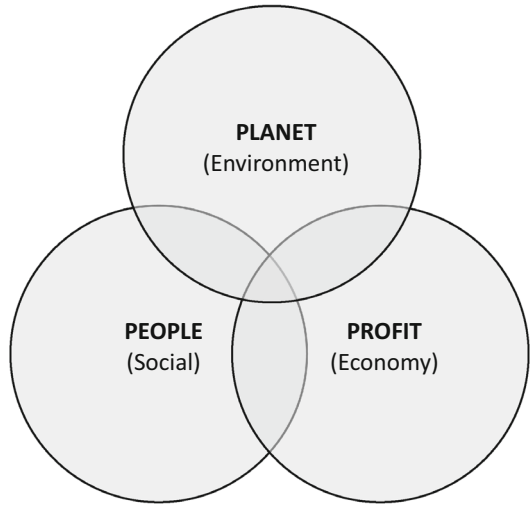
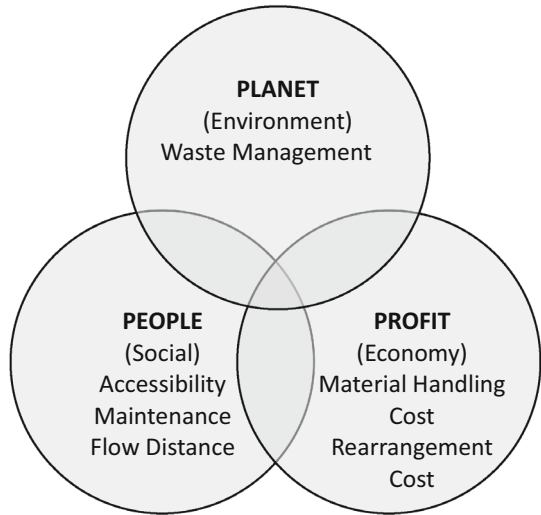


Fig. 2 3-P's framework of sustainable SDFLP



integrates meta-heuristics techniques viz. SA, CSA, Hybrid FA/CSA to generate layouts followed by applying DEA to identify efficient layouts among the generated ones, and finally applying MADM approaches such as TOPSIS, IRP and AHP in association with aggregate ranking methods viz. Borda–Kendall and integer linear programming (ILP) considering six different criteria i.e. material handling cost, flow distance, rearrangement cost, accessibility, maintenance and waste management to design SSDFLP. Our contribution lies in addressing the FLP problem from a sustainability perspective (investigating economic, social, and environmental perspectives) (Yang et al. 2013; Sacaluga and Frojan 2014; Lieckens et al. 2015) while incorporating both quantitative and qualitative criteria (Moslemipour and Lee 2011; Garcia-Hernandez 2013; García-Hernández 2015; Yang et al. 2013; Tayal and Singh 2014).

The paper is organized as follows. Section 2 reviews the past literature and underlines the research gaps. Section 3 discusses the mathematical formulation of SDFLP, the qualitative

and qualitative parameters of sustainability and formulates the Sustainable SDFLP model. Section 4 elucidates the methodology to identify the optimum layout. Section 5 provides the numerical illustration using problem size, $N = 12$, time period, $T = 5$ and Gaussian distribution product demand. Section 6 discusses our results in light of the literature, whereas Sect. 7 summarizes our research findings.

2 Literature review

2.1 Sustainable operations management

Elliott (2001) has argued the role of operations management in sustainability, whereas in a later study (Drake and Spinler 2013) have argued that the future role of operations management needs to address issues related to the 3Ps, that is, planet, people and profit. Gupta (1995) have discussed the need for aligning environmental strategy with operations strategy. To address environmental problems Gupta and Sharma (1996) have proposed the term ‘environmental operations management’ (EOM), defined as the integration of environmental management with operations management principles. Sarkis (2001) further attempted to extend the EOM definition by focusing on tools such as: design for environment (DOE), green supply chains, total quality environmental management (TQEM), and reverse logistics. However, the most notable contribution towards the emerging field of sustainable operations management (SOM) was by Kleindorfer et al. (2005), who have identified the scope for operations management surrounding around three Ps (planet, people, and profit) in three areas: (1) Green product and process development, (2) Lean and green operations management and (3) Remanufacturing and closed-loop supply chains. Linton et al. (2007) underlined the implications of sustainability for supply chains, whereas Nunes and Bennett (2010) have noted the importance paid by manufacturers to issues related to green buildings, eco-design, green supply chains, reverse logistics and innovation. In a recent study Yu and Ramanathan (2015) have investigated two dimensions of green operations (i.e. internal green practices and green product/process design) on environmental performance under the influence of stakeholder’s pressures.

Within sustainable operations, facility layout design has been identified as having an essential impact on the operations performance, especially within manufacturing systems (Yang et al. 2013), and is explicated in the next section.

2.2 Facility layout design

Layout design is a strategic issue (Timothy 1998; Yang et al. 2013) and has a significant impact on the performance of a manufacturing or service industry (Canen and Williamson 1998; Yang et al. 2013). Engineers, workers, and decision makers have attempted to obtain the best layout with the view to optimize material flow distance, total product produced, cycle time, waiting time, facility utilization, etc. According to Tompkins et al. (2003), total MHC is an appropriate measure to evaluate the efficiency of the layout and forms 20–50% of the total manufacturing cost. Researchers classified the facility layout problem into static and stochastic facility layout problem. In today’s manufacturing environment product flow is uncertain over multi time period hence the facility layout needs to be adept to these changes. This type of facility layout problem is referred to as stochastic dynamic facility layout problem (SDFLP). SDFLP is a combinatorial optimization and non-deterministic polynomial complete problem (for FLP see O’Brien and Abdel 1980; Tompkins et al. 1996; Kusiak and Heragu 1987; Rosenblatt and Lee 1987; Singh and Sharma 2006; Singh and

Singh 2010). [McKendall et al. \(2006\)](#) have addressed the need for building dynamic facility layout problem (DFLP) due to demand uncertainty and supply uncertainty. [Balakrishnan and Cheng \(2009\)](#) have further argued to develop DFLP algorithms so that demand uncertainty does not influence the algorithms performance. [Lieckens et al. \(2015\)](#) have argued the need for sustainable aspect, which includes moral hazards while locating the maintenance services with remanufacturing unit location and its layout design. Recently, [Akash and Singh \(2016\)](#) applied big data analytics to optimize stochastic dynamic facility layout problem.

However, the majority of the literature on stochastic FLP literature uses mostly quantitative criteria including shape ratio, material handling cost and rearrangement cost, adjacency score, and space demand as well as qualitative criteria such as flexibility and quality ([Les and Fariborz 1998](#); [Albert et al. 2010](#); [Moslemipour and Lee 2011](#); [Yang et al. 2013](#); [Tayal and Singh 2014](#)) but apart from few exceptions focusing mainly on energy-efficient facility layouts ([Yang et al. 2013](#); [Sacaluga and Frojan 2014](#)), literature has not yet fully discussed social and environmental issues which are key to sustainable operations management, and, has not looked into the generation of aggregate ranking to obtain a desirable layout that has a highest degree of satisfaction for quantitative and qualitative sustainability parameters. To address these gaps, this study proposes a sustainable SDFLP model that considers both qualitative and quantitative criteria under stochastic product demand flow over multi time period, using the hierarchical framework of-meta heuristic, multiple attribute decision making (MADM) techniques and consensus ranking method. The model is discussed in the next sections. More details of facility layout can be seen from [Borda \(1781\)](#), [Kendall \(1962\)](#), [Rosenblatt \(1979\)](#), [Dutta and Sahu \(1982\)](#), [Kirkpatrick et al. \(1983\)](#), [Fortenberry and Cox \(1985\)](#), [Hajek \(1988\)](#), [Khare et al. \(1988a, b\)](#), [Zouein and Tommelein \(1999\)](#), [Sinuany-Stern et al. \(2000\)](#), [Yang and Kuo \(2003\)](#), [Kulturel-Konak et al. \(2004\)](#), [Bruglia et al. \(2004, 2005\)](#), [Kulturel-Konak \(2007\)](#), [Tavana et al. \(2007\)](#), [Kia et al. \(2012\)](#), [Moslemipour et al. \(2012\)](#), and [Date et al. \(2014\)](#).

3 Sustainable SDFLP formulation

The various aspects of sustainable SDFLP formulation—mathematical equations, quantitative and qualitative factors of sustainability, are discussed in the next sub-sections.

3.1 Mathematical formulation of SDFLP

FLP was modeled as quadratic assignment problem (QAP) by [Koopmans and Beckman \(1957\)](#), given in Eqs. (1)–(4). [Balakrishnan et al. \(1992\)](#) provided the QAP mathematical model for dynamic facility layout problem (DFLP), including the rearrangement cost, is given in Eqs. (5)–(9).

$$C(\pi) = \sum_{i=1}^N \sum_{j=1}^N \sum_{l=i}^N \sum_{q=1}^N f_{ij} d_{lq} x_{il} x_{jq} \tag{1}$$

Subject to:

$$\sum_{i=1}^N x_{il} = 1; \quad \forall l \tag{2}$$

$$\sum_{l=1}^N x_{il} = 1; \quad \forall i \tag{3}$$

$$x_{il} = \begin{cases} 1, & \text{if facilities } i \text{ is assigned to location } l \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

Notations	Description
i, j	Index for facilities ($i, j = 1, 2, \dots, N$); $i \neq j$
l, q	Index for locations ($l, q = 1, 2, \dots, N$); $l \neq q$
f_{ij}	Flow of material between facilities i to j
f_{tij}	Flow of material between facilities i to j in time period t
d_{lq}	Distance between locations l and q
N	Number of facilities
$C(\pi)$	Total MHC for layout π
$E(\pi)$	Expected value of a π -th layout
$Var(\pi)$	Variance of a π -th layout
$Pr(\pi)$	Probability of a π -th layout
Z_p	Standard Z (random variable) value for percentile p
$U(\pi, p)$	Maximum value upper bound of $C(\pi)$ with confidence level p
K	Index for parts ($k = 1, 2, \dots, K$)
M_{ki}	Operation number for the operation done on part k by facility i
D_{kt}	Demand for part k in period t
B_k	Transfer batch size for part k
C_{tk}	Cost of movements for part k in period t
Z	Random variable
a_{tilq}	Fixed cost of shifting facility i from location l to location q in period t
R_c	Rearrangement cost
MHC	Material handling cost
μ_{ij}	Mean of product demand
σ_{ij}^2	Variance of product demand

Dynamic FLP is modeled as shown below:

$$\begin{aligned} \text{Minimize } C(\pi) = & \sum_{t=1}^T \sum_{i=1}^M \sum_{j=1}^M \sum_{l=1}^M \sum_{q=1}^M f_{tij} d_{lq} x_{til} x_{tjq} \\ & + \sum_{t=2}^T \sum_{i=1}^M \sum_{l=1}^M \sum_{q=1}^M a_{tilq} y_{tilq} \end{aligned} \tag{5}$$

Subject to:

$$\sum_{i=1}^M x_{til} = 1; \quad \forall t, l \tag{6}$$

$$\sum_{l=1}^M x_{til} = 1; \quad \forall t, i \tag{7}$$

$$x_{til} = \begin{cases} 1, & \text{if facilities } i \text{ is assigned to location } l \text{ in period } t \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

$$y_{tilq} = x_{(t-1)il} \times x_{tiq} \tag{9}$$

The product flows between facilities are generally an expression of demand, which could be static, dynamic or uncertain. [Rosenblatt and Kropp \(1992\)](#) first proposed an analytical formulation of static stochastic facility layout problem (SFLP). The uncertainty treatment in the facility layout has gained prominence in the present scenario where the product demand or the product mix is not known deterministically but stochastically. DFLP mathematical model can be modified for the Stochastic DFLP model by assuming product demand to be random variable and is expressed as probability distribution function (PDF) with known mean and variance. Equation (5) is modified for stochastic process and $C(\pi)$ becomes a function of random variables. Here, f_{tij} is changed to stochastic variable due to uncertainty of demand with mean μ_{ij} and variance σ_{ij}^2 . Objective function for SDFLP includes MHC and R_c and given in Eq. (10) ([Moslemipour and Lee 2011](#)).

$$\text{Minimize } \left\{ \begin{aligned} & \left[\frac{\sum_{t=1}^T \sum_{i=1}^N \sum_{j=1}^N \sum_{k=1}^N \frac{E(D_{tk})}{B_k} C_{tk} \sum_{l=1}^N \sum_{q=1}^N d_{lq} x_{til} x_{tjq}}{\sum_{t=1}^T \sum_{i=1}^N \sum_{j=1}^N \sum_{k=1}^K \frac{\text{Var}(D_{tk})}{B_k^2} C_{tk}^2 \left(\sum_{l=1}^N \sum_{q=1}^N d_{lq} x_{til} x_{tjq} \right)^2} \right]^2 \\ & + Z_p \sqrt{\sum_{t=1}^T \sum_{i=1}^N \sum_{j=1}^N \sum_{k=1}^K \frac{\text{Var}(D_{tk})}{B_k^2} C_{tk}^2 \left(\sum_{l=1}^N \sum_{q=1}^N d_{lq} x_{til} x_{tjq} \right)^2} \\ & + \left[\sum_{t=2}^T \sum_{i=1}^N \sum_{l=1}^N \sum_{q=1}^N a_{tilq} x_{(t-1)il} x_{tjq} \right] \end{aligned} \right\} \tag{10}$$

Subject to:

$$\sum_{i=1}^N x_{til} = 1; \quad \forall t, l \tag{11}$$

$$\sum_{l=1}^N x_{til} = 1; \quad \forall t, i \tag{12}$$

$$x_{til} = \begin{cases} 1, & \text{if facilities is assigned to location in period } t \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

$$|M_{ki} - M_{kj}| = 1 \tag{14}$$

3.2 Quantitative and qualitative attributes for sustainability

A preliminary review of the literature and experts’ opinion was conducted to determine the quantitative and qualitative design attributes of the model, as well as the sustainability pillars to be included. The quantitative attributes included *material handling cost (MHC)*, *flow distance* and *rearrangement cost*. Qualitative attributes included *accessibility*, *maintenance*, and *waste management*. The economic, social, and environmental pillar of sustainability were included as follows: (i) for the *economic pillar* the model included *MHC*, *Rearrangement cost (R_c)* and *flow distance*. *Material handling cost (MHC)*, is calculated as product of flow of material between the facilities and travelled distance between the locations. Due to change in product demand there is a change in flow of materials from one time period to next. *Rearrangement Cost (R_c)*, is the variable cost of moving facility *i* in time period *t* to facility *j* in time period *t + 1*. *Flow distance*, is equal to the sum of the products of flow volume and rectilinear distance between the centroids of two departments. (ii) For the *social pillar* the model included *maintenance* and *accessibility*. *Maintenance* is related to a number of activities like upgradation of the existing facility, recycling, waste disposal in the built-in environment so as to reduce the level of hazards, pollution and consumption of environmental resources. *Accessibility* involves the required space for material handling path, personal flow (operator path), information flow and equipment flow. (iii) For the *environmental pillar* the model included *waste management*. *Waste management* involves all those activities or actions required to manage waste from its inception to its disposal. Waste flow time is the time required for the movement of waste between two departments (machines).

3.3 Sustainable SDFLP formulation

The sustainable SDFLP involves assigning facilities to location to satisfy the multiple quantitative and qualitative parameters. For sustainable facility layout design problem in a stochastic demand, MHC, R_c, flow distance and waste are minimized while accessibility and maintenance are maximized. Figure 3 presents the flow chart to model sustainable stochastic dynamic facility layout problem (SSDFLP) and shows major stages involved in modeling the proposed SSDFLP. The methodology to solve the proposed sustainable SDFLP is discussed in the following section.

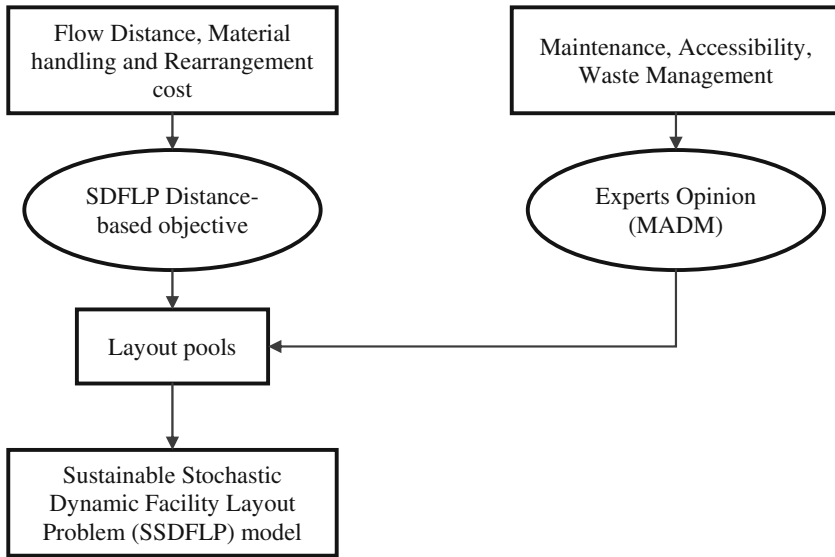


Fig. 3 Flow chart of SSDFLP

4 Methodology to solve sustainable SDFLP

Malakooti (1989) presented three methodologies for solving MO-FLP problem which are described below:

1. Generating a set of efficient layout alternatives by varying the weights assigned to the objective functions and presenting it to the decision maker,
2. Assessing the decision-maker's preferences first, then generating the best layout alternative, and
3. Using an interactive method to find the best layout alternative.

This paper adds to the aforementioned methodologies by proposing a fourth methodology, that is, ranking a pool of layouts using expert's opinion and MADM techniques to find a practical facility layout satisfying the qualitative and quantitative criteria. The proposed approach includes three steps: (1) generating pool of optimal layouts, (2) ranking the layout using expert opinion and various MADM techniques, and (3) subjectivity reduction in ranks using aggregate ranking method. To generate the pool of optimal layouts either meta-heuristic techniques or computer aided software can be used. The layouts are assessed by the experts based on the 3Ps of sustainability.

Evaluating and analyzing a pool of layout is a challenge for any expert therefore a reduced set of layouts was needed. According to Tompkins et al. (2003), total MHC (sum of material handling cost and rearrangement cost) forms 20–50% of the total manufacturing cost, hence the layouts were evaluated on material handling cost, rearrangement cost and flow distance which forms the Profit factor of sustainable SDFLP. Data envelopment analysis (DEA) technique was applied. This reduced set of layout need to be ranked for which experts were involved for computing the weights of criteria's (3P's). Both MCDM techniques and expert opinions were applied to get the rank of the layouts. Ranking of conflicting quantitative and qualitative criteria's of 3Ps is highly subjective; to overcome subjectivity, aggregate ranking is applied. The description of the methodology to solve proposed sustainable SDFLP

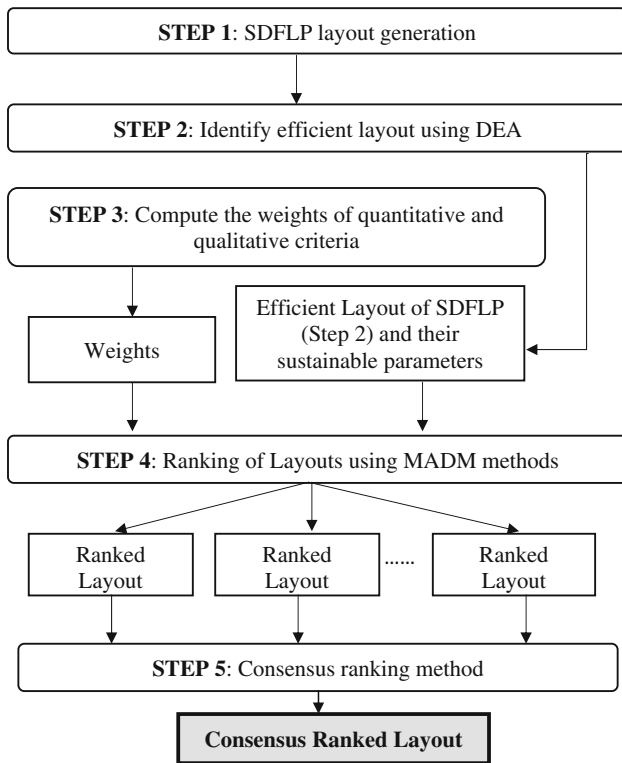


Fig. 4 Methodological framework of proposed SSDFLP

is presented in Fig. 4. The detailed description of each step is provided in the following paragraphs.

Step 1: SDFLP layout generation

This step uses either commercial computer-aided planning tools such as Spiral, ALDEP, BLOKPLAN or metaheuristic techniques (SA, CSA, Hybrid FA/CSA) to generate layout alternatives, as well as a collection of quantitative performance data. The techniques SA, CSA and Hybrid FA/CSA are used to generate a pool of layouts and its data for quantitative parameters is collected as shown in Figs. 5, 6, and 7, respectively. Detailed description on meta-heuristic techniques for solving SDFLP can be found in [Tayal and Singh \(2015\)](#), [Tayal and Singh \(2016a, b\)](#).

Step 2: identify efficient SDFLP layouts using DEA

Data envelopment analysis (DEA) is applied to identify set of efficient layouts among all possible layouts obtained in Step 1. DEA is a non-parametric approach in operations research that does not require any assumptions about the functional form for the estimation of production frontiers. Assume that there are n decision-making units (DMUs) to be evaluated. Each DMU consumes varying amount of m different inputs to produce s different outputs. Following are the notations used in the DEA.

Specifically, DMU_k consumes amount X_{ik} of input i and produces amount Y_{rk} of output r , that can be incorporated into an efficiency measure—the weighted sum of the outputs

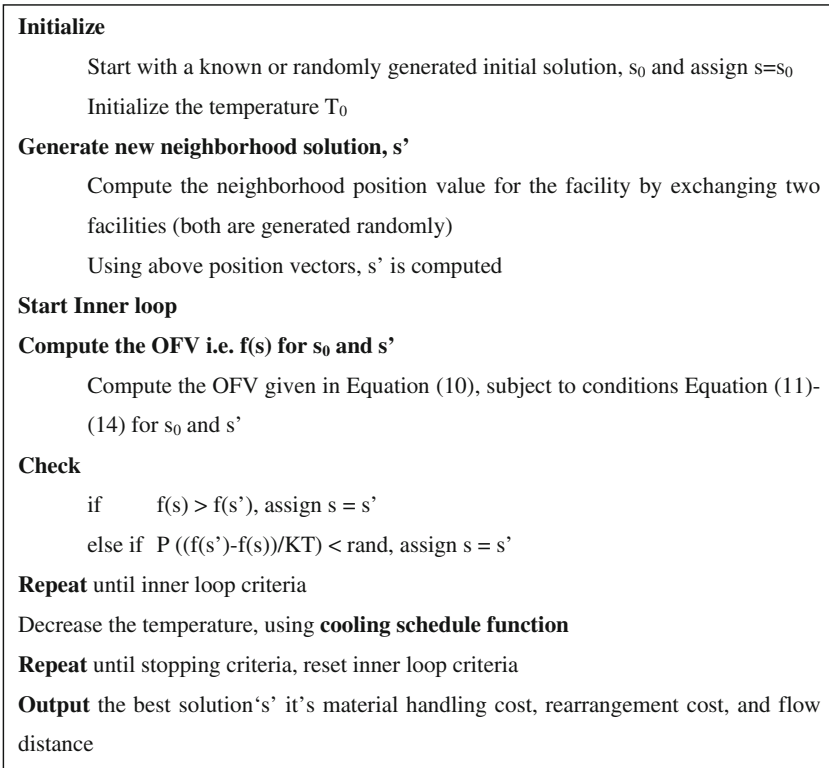


Fig. 5 Simulated annealing for solving SDFLP

Notations	Description
DMU_k	kth decision making unit (DMU), $k = 1, 2, \dots, n$
X_{ik}	ith input for the kth DMU, $i = 1, 2, \dots, m$ and $k = 1, 2, \dots, n$
Y_{rk}	rth output for the kth DMU, $r = 1, 2, \dots, s$ and $k = 1, 2, \dots, n$
v_i	Associated weight for the ith input, $i = 1, 2, \dots, m$
u_r	Associated weight for the rth output, $r = 1, 2, \dots, s$
h_k	Efficiency score ($h_k \leq 1$)

divided by the weighted sum of the inputs $h_k = \sum u_r Y_{rk} / \sum v_i X_{ik}$. This definition requires a set of factor weights u_r and v_i which are the decision variables. Each DMU_k is assigned the highest possible efficiency score ($h_k \leq 1$) by choosing optimal weights for the outputs and inputs. DEA often generates several 100% efficient frontiers among the DMU's resulting in discrepancy to identify the top choice.

The data from Step 1 is taken as DMU's with 3 inputs (material handling cost, rearrangement cost and flow distance) and 1 output (set equal to 1) for identifying efficient layouts using DEA.

Step 3: compute weights for quantitative and qualitative criteria

Qualitative and quantitative criteria may be complex and conflicting, hence weight importance is provided by experts using analytic hierarchy process (AHP) (Saaty 1980). AHP is a popular

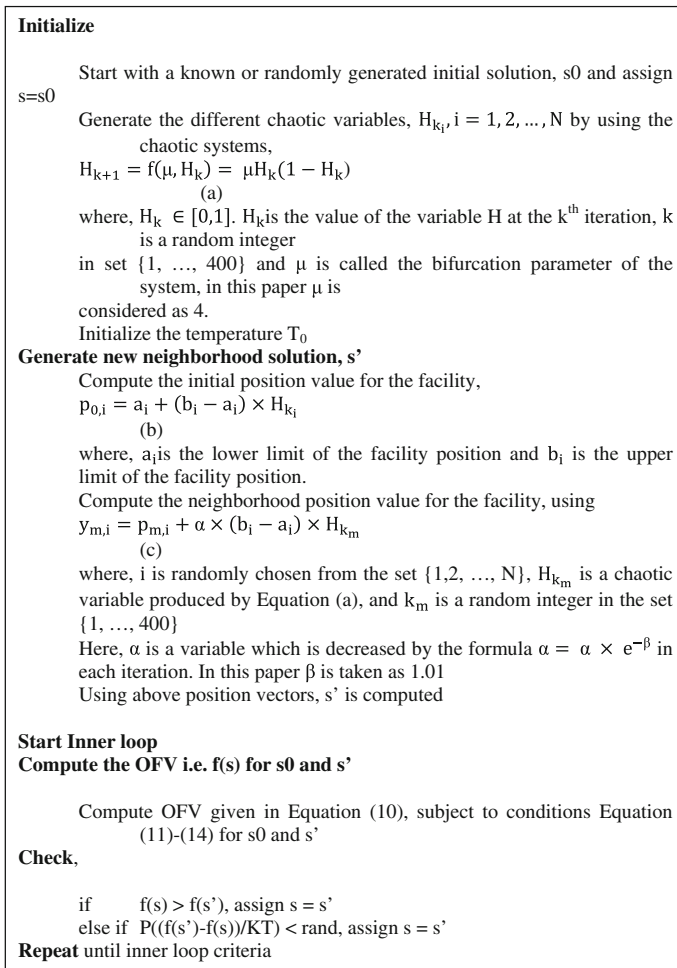


Fig. 6 Chaotic simulated annealing for solving SDFLP

technique that has been employed to model subjective decision-making processes based on multiple criteria. However, the importance of each criterion is not necessarily equal. To resolve this problem, Saaty uses the eigenvector method to determine the relative importance (weights) among the various criteria based on the pairwise comparison matrix in AHP.

If $A = [a_{ij}]$ is a positive reciprocal matrix, then the geometric mean of each row $r_i = \left(\prod_{j=1}^n a_{ij}\right)^{1/n}$. Saaty defined λ_{\max} as the largest eigenvalue of A , and the weights w_i as the components of the normalized eigenvector corresponding to λ_{\max} , where $w_i = r_i / (r_1 + r_2 + \dots + r_n)$.

The decision maker has to redo the ratios when the comparison matrix fails to pass the consistency test, because the lack of consistency in decision-making can lead to inconsistent results. Hence, a consistency index to ensure that AHP's pairwise comparison method is consistent needs to be calculated. The consistency index is given in Eq. (15):

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{15}$$

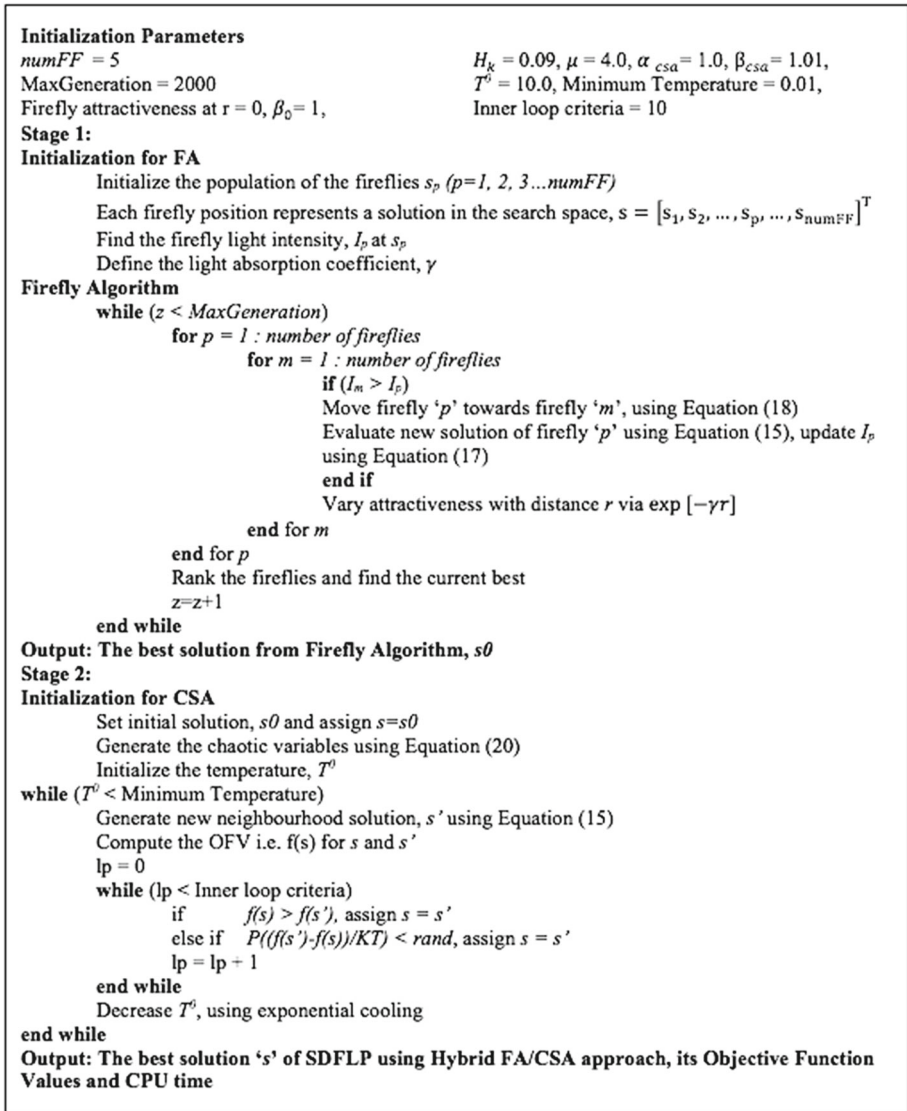


Fig. 7 Hybrid FA/CSA for solving SDFLP (Tayal and Singh 2016c)

where λ_{\max} denotes the maximal eigenvalue of the matrix R . When matrix R is consistent then $\lambda_{\max} = n$ and $CI = 0$. Consistency ratio ($=CI/RI(n)$) is the ratio of the consistency index to the corresponding random index. Following Saaty (1980), a consistency ratio (CR) of 0.1 or less is acceptable. Hence, weights for the 6 criteria, quantitative attributes (material handling cost, the rearrangement cost and flow distance) and qualitative attributes (accessibility, maintenance and waste management), were obtained using AHP.

Step 4: ranking of Layouts using MADM methods

MADM deals with the problem of choosing an option from the set of alternatives, which are characterized in terms of their attributes. Here, we provide a conceptual description of MADM techniques used in this paper.

- TOPSIS—Euclidian and Manhattan

A multi criteria decision making (MCDM) problem can be expressed in a matrix format, in which columns indicate attributes rows list the competing alternatives. Alternatives are represented by (A_1, A_2, \dots, A_m) and criteria by (C_1, C_2, \dots, C_n) . An element x_{ij} of the matrix indicated the performance rating of the i th alternatives, A_i , with respect to the j th criteria, C_j , as shown in Eq. (16):

$$D = \begin{matrix} & C_1 & C_2 & C_3 & \dots & C_n \\ A_1 & x_{11} & x_{12} & x_{13} & \dots & x_{1n} \\ A_2 & x_{21} & x_{22} & x_{23} & \dots & x_{2n} \\ A_3 & x_{31} & x_{32} & x_{33} & \dots & x_{3n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & x_{m1} & x_{m2} & x_{m3} & \dots & x_{mn} \end{matrix} \quad (16)$$

Hwang and Yoon (1981) developed TOPSIS based on the concept that the chosen alternative should have the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution. The terms used are defined as follows:

Criteria: attributes $(C_j, j = 1, 2, \dots, n)$ should provide a means of evaluating the levels of an objective. For SDFLP attributes are MHC, rearrangement cost, flow distance, accessibility, maintenance and waste management.

Alternatives: these are synonymous with ‘options’ or ‘candidates’. Alternatives $(A_i, i = 1, 2 \dots m)$. Alternatives are the efficient layouts obtained from Step 2.

Criteria weights: weight values (w_j) represent the relative importance of each attribute to the others. $W = \{w_j | j = 1, 2, \dots, n\}$. Attributes weights are obtained from Step 3.

Normalization: normalization seeks to obtain comparable scales, which allows attribute comparison. The vector normalization approach divides the rating of each attribute by its norm to calculate the normalized value of x_{ij} as defined in Eq. (17):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}, \quad i = 1, \dots, m; j = 1, \dots, n. \quad (17)$$

Figure 8 provides the pseudo code of TOPSIS based on Euclidian and Manhattan distance for ranking the layouts.

- AHP

AHP is also applied to rank the layouts. For each of the criteria a pair wise comparison matrix of the efficient layouts is formulated and consistency index is computed. Given the information of the relative importance i.e. weights of each criteria (obtained in Step 3) and preferences, mathematical procedure is used to synthesize the information and provide priority ranking of all alternatives (layouts). The overall priority of each decision alternative is obtained by summing the product of the criteria priority i.e. weights times the priority of the decision alternative with respect to the criteria.

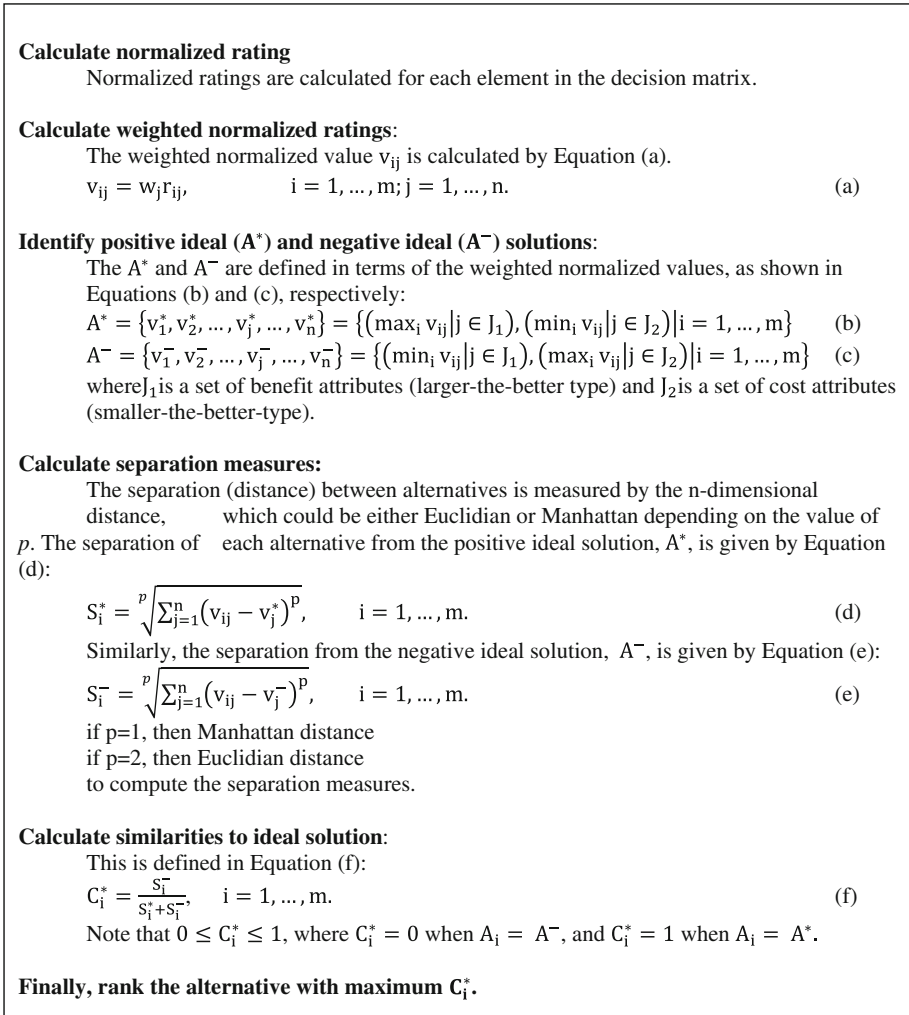


Fig. 8 Pseudo code of TOPSIS method for ranking layouts

• **IRP**

To overcome the limitations of intuitive process and rational choice process, interpretive ranking process (IRP) proposed by (Sushil 2009) is applied. This technique uses the strengths of both the processes of decision making and complementing the limitations of each one by the other. Steps of IRP methods are shown in Fig. 9.

TOPSIS (Euclidian and Manhattan distance), AHP, and IRP are applied for ranking efficient layouts obtained by the DEA approach in Step 2 taking into account the quantitative and qualitative factors along with their weights.

Step 5: consensus ranking method

To obtain the ranking of multiple decision makers regarding the layouts aggregation techniques need to be used. There are several techniques such as Borda–Kendall, Integer linear model for rank aggregation, Beck and Lin (1983), Cool and Kress to yield a compromise

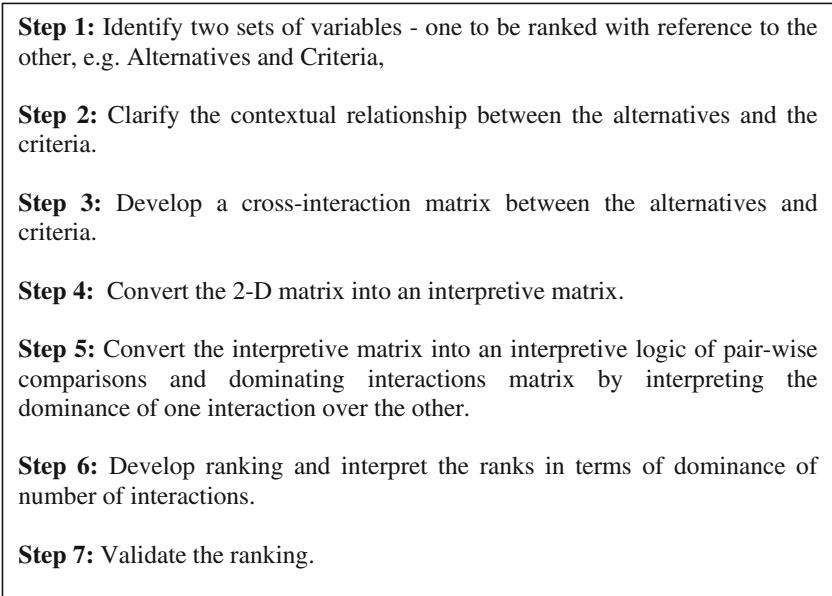


Fig. 9 Steps of IRP method for ranking layouts

or aggregate ranking. In this paper, we used 2 techniques—(1) Borda–Kendall (Cook and Seiford 1982; Cook and Kress 1985) and (2) Integer linear model for rank aggregation (Kaur et al. 2017).

1. *Borda–Kendall (BAK) technique* it is the most widely used to formulate and solve consensus ranking from various MADM algorithms. In this method, we calculate the positional mean value of the ranks for each project (layout) over all decision makers (MADM algorithms). The project with the lowest combined score is most preferred and the project with the highest combined score is least preferred.
2. *Integer linear Programming (ILP) for rank aggregation* let there be n number of efficient facility, which are ranked according to m different MADM techniques. An integer linear model for rank aggregation ranks different MADM techniques into consensus ranking is explained below: following are the notations used,

- Y_i Final aggregated ranking of facility i
- X_{ij} Rank of facility i using j th multi-attribute decision making (MADM) technique
- n Number of facilities
- m Number of MADM techniques

Objective function

$$\text{Min } Z = \sum_{i=1}^n \sum_{j=1}^m |X_{ij} - Y_i| \tag{18}$$

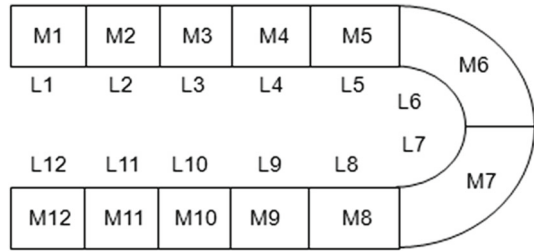
Subject to

$$1 \leq Y_i \leq n \quad \forall i (1, 2, \dots, n) \tag{19}$$

$$Y_i \neq Y_k \quad \forall i, k \text{ such that } i \neq k \tag{20}$$

$$Y_i \text{ is integer} \quad \forall i (1, 2, \dots, n) \tag{21}$$

Fig. 10 U-shaped facility layout for $N = 12$



The objective function of the model as shown in Eq. (18) minimizes the deviation of the final ranking from individual rankings from various MCDM techniques. Equation (19) restricts the ranking of n suppliers from 1 to n only. Equation (20) ensures that no two suppliers are given same rank; hence every supplier is given a different rank. Integer value of the rank is ensured by Eq. (21).

5 Numerical illustration

To validate the sustainable SDFLP formulation and its solution methodology, the SDFLP example considered has the product demand to be Gaussian distribution for facility (machine) size, $N = 12$, (U-shaped layout is shown in Fig. 10) and multiple time periods, $T = 5$. The data set has been taken from (Moslemipour and Lee 2011).

The adjacency matrix, separation matrix and waste flow time matrix are empirically generated (refer “Appendix 1”). The efficient layout along with adjacency, separation and waste flow time matrix are used by the experts to compute the quantifiable values of accessibility, maintenance and waste management parameters, which form a pool of sustainable layouts. The flow chart shown in Fig. 11 presents the entire methodology to solve SSDFLP for the numerical illustration considered. Figure 11 also shows various tables i.e. from Tables 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12 generated while applying the proposed methodology to solve SSDFLP. Table 1 shows the pool of thirty layouts generated applying step 1.

DEA using CCR (Charnes et al. 1978) model is applied to 30 layouts (as independent DMU’s with 3 inputs (material handling cost, rearrangement cost and flow distance) and 1 output (set equal to 1) for identifying the efficient layouts, Table 2 extrapolates the efficiency scores of the layouts.

Weights (sum of weights equal to 1) for each attribute were computed using AHP (preferences of expert) as given in Tables 3 and 4. It can be seen that the experts have given importance to MHC (profit—economic pillar) then Maintenance (people—social pillar) and waste management (planet—environmental pillar). This shows that all 3Ps of sustainability are important for designing a sustainable SDFLP.

Finally, 9 efficient layouts were identified, which are considered as alternatives (A_1, A_2, \dots, A_9) for ranking based on six attributes—namely, MHC, rearrangement cost, flow distance, accessibility, maintenance and waste management—using TOPSIS—Euclidian distance, TOPSIS—Manhattan Distance, AHP and IRP methods. Four different rankings of the 9 layouts are obtained which are summarized in Tables 5, 6, 7, 8 and 9. The rankings of the layout are based on the weights given to 6 criteria and the expert opinion, which changes as preferences or weights assigned to the criteria are varied. The rankings of layout are not unique therefore aggregate ranking methods need to be applied to find the

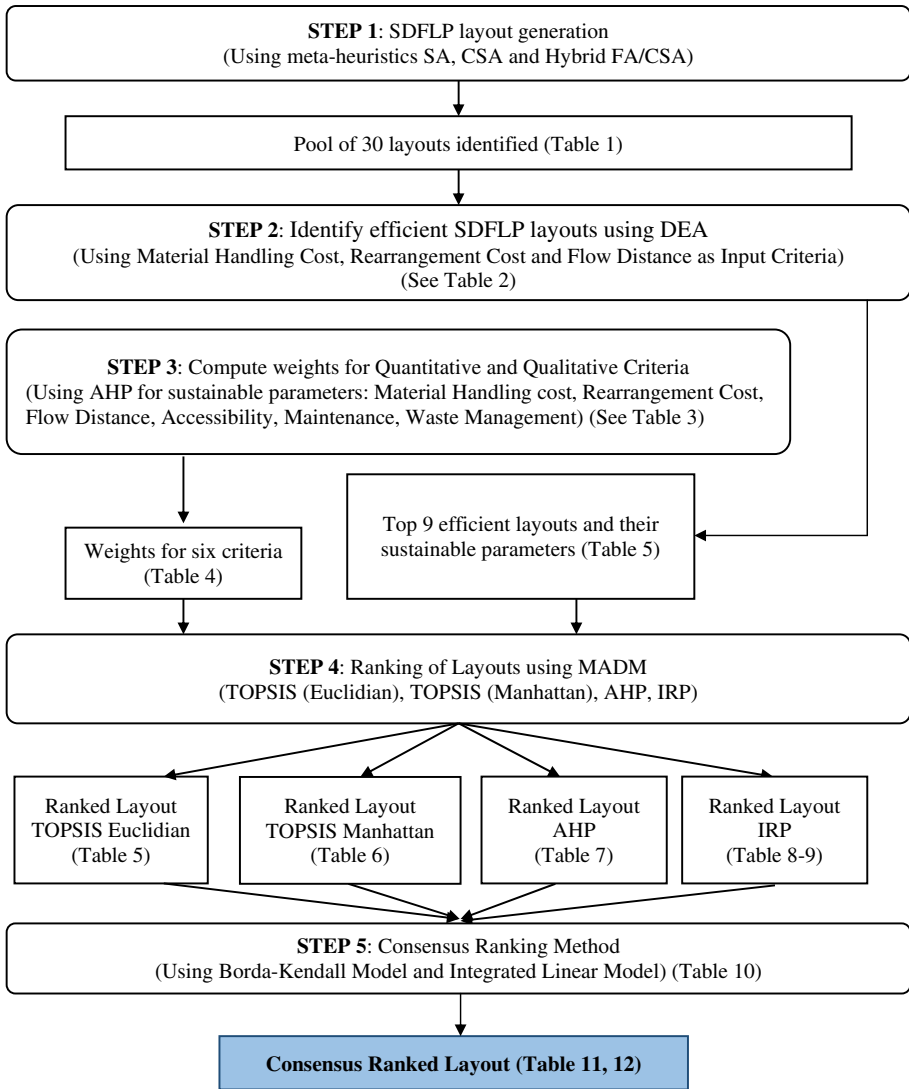


Fig. 11 Flow chart to solve SSDFLP of the numerical illustration

optimum (and most suitable) layout. Borda–Kendall (BAK) method and ILP were applied to obtain the consensus ranking as shown in Table 10.

Table 11 gives the ranking of layout based on BAK method and Table 12 gives the ranking of layout based on ILP. “Layout 29” (BAK) and “Layout 20” (ILP) gets an aggregate rank score “1”. The corresponding parameter values of both layouts are very close, thus, giving the best trade-off balancing all the three pillars of sustainable operations. Hence, the proposed methodology facilitates the decision maker in identifying an optimal SDFLP which satisfy the sustainability factors. Data for the numerical illustration is provided in “Appendix 1” (from Table 13 to Table 15). All the nine efficient facility layouts are shown in “Appendix 2” (from Tables 16, 17, 18, 19, 20, 21, 22, 23 and 24).

Table 1 Pool of layouts

#	Material handling cost	Rearrangement cost	Flow distance
Layout 1	1,182,794.94	44,000.00	1960.00
Layout 2	1,214,292.75	35,000.00	2010.00
Layout 3	1,217,821.67	40,000.00	2030.00
Layout 4	1,199,635.24	46,000.00	1960.00
Layout 5	1,220,216.58	36,000.00	2020.00
Layout 6	1,243,861.74	35,000.00	2060.00
Layout 7	1,242,892.22	27,000.00	2100.00
Layout 8	1,253,106.47	29,000.00	2130.00
Layout 9	1,242,367.90	34,000.00	2060.00
Layout 10	1,211,549.71	47,000.00	2010.00
Layout 11	1,220,786.80	47,000.00	2000.00
Layout 12	1,247,686.14	48,000.00	2030.00
Layout 13	1,232,851.06	37,000.00	2110.00
Layout 14	1,225,323.50	31,000.00	2040.00
Layout 15	1,210,757.05	41,000.00	2010.00
Layout 16	1,223,570.79	44,000.00	2010.00
Layout 17	1,231,464.89	43,000.00	2060.00
Layout 18	1,251,542.71	47,000.00	2080.00
Layout 19	1,240,779.87	46,000.00	2060.00
Layout 20	1,224,288.63	22,000.00	2040.00
Layout 21	1,241,328.45	35,000.00	2030.00
Layout 22	1,240,195.26	46,000.00	2020.00
Layout 23	1,211,549.71	47,000.00	2010.00
Layout 24	1,238,907.82	39,000.00	2030.00
Layout 25	1,235,607.40	45,000.00	2040.00
Layout 26	1,249,402.96	45,000.00	2100.00
Layout 27	1,245,371.07	43,000.00	2030.00
Layout 28	1,227,909.04	43,000.00	2020.00
Layout 29	1,202,739.83	29,000.00	1970.00
Layout 30	1,237,646.50	44,000.00	2040.00

6 Discussion

Our interest in investigating the stochastic dynamic facility location problem was triggered by three gaps within facility layout design problem literature: firstly, the inherent uncertainties in demand and supply, which are widely noted in operations management literature (Balakrishnan and Cheng 2007, 2009; Dubey et al. 2015); secondly, the lack of studies that look into the FLP from a sustainability point of view, apart from exceptions (Yang et al. 2013; Sacaluga and Frojan 2014; Lieckens et al. 2015) and thirdly, the lack of studies in the stochastic FLP literature that use both quantitative and qualitative criteria apart from notable exceptions (Moslemipour and Lee 2011; Garcia-Hernandez 2013; García-Hernández 2015; Yang et al. 2013; Tayal and Singh 2014). We are in agreement with Yang et al. (2013) who

Table 2 Efficiency of layouts using DEA

#	Material handling cost	Rearrangement cost	Flow distance	Efficiency
Layout 1	1,182,794.94	44,000.00	1960.00	1
Layout 2	1,214,292.75	35,000.00	2010.00	1
Layout 3	1,217,821.67	40,000.00	2030.00	0.983731471
Layout 4	1,199,635.24	46,000.00	1960.00	1
Layout 5	1,220,216.58	36,000.00	2020.00	0.992997233
Layout 6	1,243,861.74	35,000.00	2060.00	0.978471475
Layout 7	1,242,892.22	27,000.00	2100.00	1
Layout 8	1,253,106.47	29,000.00	2130.00	0.986237675
Layout 9	1,242,367.90	34,000.00	2060.00	0.981641469
Layout 10	1,211,549.71	47,000.00	2010.00	0.976266125
Layout 11	1,220,786.80	47,000.00	2000.00	0.98
Layout 12	1,247,686.14	48,000.00	2030.00	0.965517241
Layout 13	1,232,851.06	37,000.00	2110.00	0.979942205
Layout 14	1,225,323.50	31,000.00	2040.00	1
Layout 15	1,210,757.05	41,000.00	2010.00	0.986506044
Layout 16	1,223,570.79	44,000.00	2010.00	0.982975272
Layout 17	1,231,464.89	43,000.00	2060.00	0.976674073
Layout 18	1,251,542.71	47,000.00	2080.00	0.961005821
Layout 19	1,240,779.87	46,000.00	2060.00	0.96934183
Layout 20	1,224,288.63	22,000.00	2040.00	1
Layout 21	1,241,328.45	35,000.00	2030.00	0.97044335
Layout 22	1,240,195.26	46,000.00	2020.00	0.975247525
Layout 23	1,211,549.71	47,000.00	2010.00	0.992728421
Layout 24	1,238,907.82	39,000.00	2030.00	0.970806553
Layout 25	1,235,607.40	45,000.00	2040.00	0.973399666
Layout 26	1,249,402.96	45,000.00	2100.00	0.962651657
Layout 27	1,245,371.07	43,000.00	2030.00	0.97044335
Layout 28	1,227,909.04	43,000.00	2020.00	0.979502382
Layout 29	1,202,739.83	29,000.00	1970.00	1
Layout 30	1,237,646.50	44,000.00	2040.00	0.971795929

Table 3 Decision matrix for criteria using AHP

Criteria	C2	C5	C6	C3	C4	C1
Rearrangement cost (C2)	1	0.1666667	0.5	2	1	0.125
Maintenance (C5)	6	1	1	9	4	1
Waste management (C6)	2	1	1	5	7	0.16666667
Flow distance (C3)	0.5	0.11111111	0.2	1	0.33333333	0.11111111
Accessibility (C4)	1	0.25	0.142857143	3	1	0.25
Material handling cost (C1)	8	1	6	9	4	1

Table 4 Weights of the six criteria obtained from AHP

Criteria	Rearrangement cost (C2)	Maintenance (C5)	Waste management (C6)	Flow distance (C3)	Accessibility (C4)	Material handling cost (C1)
Weights	0.055269867	0.273158654	0.190624245	0.029456427	0.066076118	0.38541469

suggest that simplifying practical FLP (and in our case, SSDFLP) in mathematical models or simulation models for objective optimization (Ertay et al. 2006; Yang and Hung 2007) needs to be complemented by qualitative criteria. Even though there are studies using qualitative criteria in conjunction with quantitative ones, they are not focusing on sustainability, rendering thereby our paper one of the first studies, if not the first, to look into the FLP problem from a sustainability perspective.

Therefore, our contribution lies in addressing these gaps; we propose and provide a *sustainable stochastic dynamic facility layout problem (SDFLP)* that uses both qualitative and quantitative factors under stochastic product demand flow over multi time period for the three pillars of sustainability (economic, social, and environmental), using the hierarchical framework of metaheuristic, MCDM techniques and consensus ranking method. Our methodology attempts to integrates metaheuristics (SA, CSA, hybrid Fa/CSA), DEA (to get efficient layouts), TOPSIS, AHP and IRP (for MCDM) and aggregate ranking (Borda–Kendall method and ILP) for six criteria i.e. MHC, flow distance, rearrangement cost, accessibility, maintenance and waste management.

7 Conclusion

The layout design problem is a strategic issue and has significant impact to the efficiency of a manufacturing system. The paper proposes a novel method to design and solve facility layout problem considering both qualitative and quantitative factors under stochastic product demand flow over multi time period is proposed, using hierarchical framework of-meta heuristic, MADM techniques and consensus ranking method. The proposed methodology for sustainable layout integrates meta-heuristics techniques viz. SA, CSA, Hybrid FA/CSA to generate layouts followed by applying DEA to identify an efficient layouts among the generated ones, and finally applying MADM approaches such as TOPSIS, IRP and AHP in association with aggregate ranking methods viz. Borda–Kendall and integer linear programming (ILP) considering six different criteria.

The effective systematic decision-making described in this paper help the facility designer to reduce the risk of choosing a poor layout design. Thus, the 3 pillars of sustainability were addressed for facility layout operations. The current research provides new insights for designing sustainable stochastic layouts. The proposed methodology is different from conventional methods where the environment and social outcomes are dealt as corrective action after designing the layout. Here, an inclusive approach is undertaken to design SSDFLP.

Table 5 Ranking using TOPSIS (Euclidian)

#	Material handling cost	Rearrangement cost	Flow distance	Accessibility	Maintenance	Waste management	C_i	Rank
Layout 1	1,182,794.94	44,000.00	1960.00	353.00	296.00	70.50	0.2630691457	9
Layout 2	1,214,292.75	35,000.00	2010.00	371.00	290.00	73.40	0.2714958234	8
Layout 4	1,199,635.24	46,000.00	1960.00	349.00	329.00	72.10	0.3918011919	5
Layout 5	1,220,216.58	36,000.00	2020.00	349.00	300.00	69.60	0.3239701548	6
Layout 7	1,242,892.22	27,000.00	2100.00	385.00	300.00	66.80	0.4934014126	4
Layout 14	1,225,323.50	31,000.00	2040.00	357.00	319.00	63.50	0.6202121921	3
Layout 20	1,224,288.63	22,000.00	2040.00	364.00	334.00	70.70	0.6961263857	1
Layout 23	1,211,549.71	47,000.00	2010.00	384.00	306.00	67.30	0.2903355416	7
Layout 29	1,202,739.83	29,000.00	1970.00	377.00	318.00	68.10	0.6262349607	2

Table 6 Ranking using TOPSIS (Manhattan)

#	Material handling cost	Rearrangement cost	Flow distance	Accessibility	Maintenance	Waste management	C_i	Rank
Layout 1	1,182,794.94	44,000.00	1960.00	353.00	296.00	70.50	0.2997688506	8
Layout 2	1,214,292.75	35,000.00	2010.00	371.00	290.00	73.40	0.2498246591	9
Layout 4	1,199,635.24	46,000.00	1960.00	349.00	329.00	72.10	0.4158912977	5
Layout 5	1,220,216.58	36,000.00	2020.00	349.00	300.00	69.60	0.3379377803	7
Layout 7	1,242,892.22	27,000.00	2100.00	385.00	300.00	66.80	0.4882771585	4
Layout 14	1,225,323.50	31,000.00	2040.00	357.00	319.00	63.50	0.6458886218	3
Layout 20	1,224,288.63	22,000.00	2040.00	364.00	334.00	70.70	0.7140908988	1
Layout 23	1,211,549.71	47,000.00	2010.00	384.00	306.00	67.30	0.3649687108	6
Layout 29	1,202,739.83	29,000.00	1970.00	377.00	318.00	68.10	0.6562867790	2

Table 7 Ranking using AHP

#	Material handling cost	Rearrangement cost	Flow distance	Accessibility	Maintenance	Waste management	Priority	Rank
Layout 1	1,182,794.94	44,000.00	1960.00	353.00	296.00	70.50	0.125442558	3
Layout 2	1,214,292.75	35,000.00	2010.00	371.00	290.00	73.40	0.063479172	8
Layout 4	1,199,635.24	46,000.00	1960.00	349.00	329.00	72.10	0.159416418	2
Layout 5	1,220,216.58	36,000.00	2020.00	349.00	300.00	69.60	0.052902153	9
Layout 7	1,242,892.22	27,000.00	2100.00	385.00	300.00	66.80	0.090040373	7
Layout 14	1,225,323.50	31,000.00	2040.00	357.00	319.00	63.50	0.112722093	5
Layout 20	1,224,288.63	22,000.00	2040.00	364.00	334.00	70.70	0.120432132	4
Layout 23	1,211,549.71	47,000.00	2010.00	384.00	306.00	67.30	0.112124318	6
Layout 29	1,202,739.83	29,000.00	1970.00	377.00	318.00	68.10	0.163440784	1

Table 8 Dominating interaction matrix of IRP

#	Layout 1	Layout 2	Layout 4	Layout 5	Layout 7	Layout 14	Layout 20	Layout 23	Layout 29
Layout 1	0	C1,C3,C5,C6	C1, C2, C4, C6	C1, C3, C4	C1, C3	C1, C3	C1, C3, C6	C1, C2	C1, C3
Layout 2	C2, C4	0	C2, C4	C1, C2, C3, C4	C1, C3, C6	C1,C3, C5	C1, C3, C4	C2	C3
Layout 4	C5	C1, C3, C5, C6	0	C1, C3,C5	C1, C3,C5	C1,C3,C5	C1, C3	C1, C2, C3, C5	C1, C3, C5
Layout 5	C2, C5, C6	C5, C6	C2, C6	0	C1, C3	C1, C3	C1,C3, C6	C2	0
Layout 7	C2, C4, C5, C6	C2, C4, C5	C2, C4, C6	C2, C4, C6	0	C2, C4	C3, C4, C6	C2, C4, C6	C2, C4, C6
Layout 14	C2, C4, C5, C6	C2, C4, C6	C2, C4, C6	C2, C4, C5,C6	C1, C3, C5, C6	0	C4, C6	C2, C5, C6	C5, C6
Layout 20	C2, C4, C5	C2, C5, C6	C2, C4, C5, C6	C2, C4, C5	C1, C2, C5	C1, C2, C5	0	C2, C5, C6	C2, C5
Layout 23	C3, C4, C5, C6	C1, C4, C5, C6	C4, C6	C1, C3, C4,C5, C6	C1, C3, C5	C1, C3, C4	C1, C3, C4	0	C4, C6
Layout 29	C2, C4, C5, C6	C1, C2, C4, C5, C6	C2, C4, C6	C1,C2, C3, C4, C5, C6	C1, C3, C5	C1, C2, C3, C4	C1, C3, C4, C6	C1,C2, C3, C5	0

Table 9 Ranking using IRP

#	Layout 1	Layout 2	Layout 4	Layout 5	Layout 7	Layout 14	Layout 20	Layout 23	Layout 29	Net dominance	Rank
Layout 1	0	4	4	3	2	2	3	2	2	-3	7
Layout 2	2	0	2	4	3	3	3	1	1	-9	8
Layout 4	1	4	0	3	3	3	2	4	3	0	6
Layout 5	3	2	2	0	2	2	3	1	0	-16	9
Layout 7	4	3	3	3	0	2	3	3	3	2	4
Layout 14	4	3	3	4	4	0	2	3	2	3	3
Layout 20	3	3	4	3	3	3	0	3	2	1	5
Layout 23	4	4	2	5	3	3	3	0	2	5	2
Layout 29	4	5	3	6	3	4	4	4	0	18	1

Table 10 Consensus ranking

Layout identifier	TOPSIS (Euclidian) ranking	TOPSIS (Manhattan) ranking	AHP ranking	IRP ranking	Consensus ranking	
					BAK	Integer linear programming (ILP)
Layout 1	9	8	3	7	7	7
Layout 2	8	9	8	8	9	8
Layout 4	5	5	2	6	4	5
Layout 5	6	7	9	9	8	9
Layout 7	4	4	7	4	5	4
Layout 14	3	3	5	3	3	3
Layout 20	1	1	4	5	2	1
Layout 23	7	6	6	2	6	6
Layout 29	2	2	1	1	1	2

Table 11 Ranked layouts using BAK

#	Material handling cost	Rearrangement cost	Flow distance	Accessibility	Maintenance	Waste management
Layout 29	1,202,739.83	29,000.00	1970.00	377.00	318.00	68.10
Layout 20	1,224,288.63	22,000.00	2040.00	364.00	334.00	70.70
Layout 14	1,225,323.50	31,000.00	2040.00	357.00	319.00	63.50
Layout 4	1,199,635.24	46,000.00	1960.00	349.00	329.00	72.10
Layout 7	1,242,892.22	27,000.00	2100.00	385.00	300.00	66.80
Layout 23	1,211,549.71	47,000.00	2010.00	384.00	306.00	67.30
Layout 1	1,182,794.94	44,000.00	1960.00	353.00	296.00	70.50
Layout 5	1,220,216.58	36,000.00	2020.00	349.00	300.00	69.60
Layout 2	1,214,292.75	35,000.00	2010.00	371.00	290.00	73.40

Table 12 Ranked layouts using ILP

#	Material handling cost	Rearrangement cost	Flow distance	Accessibility	Maintenance	Waste management
Layout 20	1,224,288.63	22,000.00	2040.00	364.00	334.00	70.70
Layout 29	1,202,739.83	29,000.00	1970.00	377.00	318.00	68.10
Layout 14	1,225,323.50	31,000.00	2040.00	357.00	319.00	63.50
Layout 7	1,242,892.22	27,000.00	2100.00	385.00	300.00	66.80
Layout 4	1,199,635.24	46,000.00	1960.00	349.00	329.00	72.10
Layout 23	1,211,549.71	47,000.00	2010.00	384.00	306.00	67.30
Layout 1	1,182,794.94	44,000.00	1960.00	353.00	296.00	70.50
Layout 2	1,214,292.75	35,000.00	2010.00	371.00	290.00	73.40
Layout 5	1,220,216.58	36,000.00	2020.00	349.00	300.00	69.60

Acknowledgements The authors would like to acknowledge the constructive and helpful comments on the previous version of the manuscript which helped to improve the presentation of the paper considerably.

Appendix 1

See Tables 13, 14 and 15.

Table 13 Adjacency matrix for the facilities

i, j	1	2	3	4	5	6	7	8	9	10	11	12
1	0	4	8	10	10	6	4	8	10	10	6	4
2	4	0	1	6	2	4	4	1	6	2	4	4
3	8	1	0	4	10	2	8	1	4	10	2	8
4	10	6	4	0	2	4	10	6	4	2	4	10
5	10	2	10	2	0	1	10	2	10	2	1	10
6	6	4	2	4	1	0	6	4	2	4	1	6
7	4	4	8	10	10	6	0	4	4	8	10	10
8	8	1	1	6	2	4	4	0	8	1	1	6
9	10	6	4	4	10	2	4	8	0	10	6	4
10	10	2	10	2	2	4	8	1	10	0	10	2
11	6	4	2	1	1	1	10	1	6	10	0	6
12	4	4	8	10	10	6	10	6	4	2	6	0

Table 14 Separation matrix for the facilities

i, j	1	2	3	4	5	6	7	8	9	10	11	12
1	0	10	8	4	10	2	10	8	4	10	2	10
2	10	0	1	8	1	10	10	1	8	1	10	10
3	8	1	0	6	1	6	8	1	6	1	6	8
4	4	8	6	0	8	8	4	8	6	8	8	4
5	10	1	1	8	0	8	10	1	1	8	8	10
6	2	10	6	8	8	0	2	10	6	8	8	2
7	10	10	8	4	10	2	0	10	10	8	4	10
8	8	1	1	8	1	10	10	0	1	1	8	1
9	4	8	6	6	1	6	10	1	0	6	6	1
10	10	1	1	8	8	8	8	1	6	0	8	8
11	2	10	6	8	8	8	4	8	6	8	0	8
12	10	10	8	4	10	2	10	1	1	8	8	0

Table 15 Waste flow matrix for the facilities

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	1.5	0.5	1.4	1.5	0.5	1	0.6	1.5	0.5	1.4	1.5
2	1.5	0	1.5	1.6	1.5	1	2	1.8	1.5	1.6	1.5	1
3	0.5	1.5	0	2	0.7	3	1.5	1.6	2	0.7	3	1.5
4	1.4	1.6	2	0	2.2	1	0.3	2	2.2	1	0.3	2
5	1.5	1.5	0.7	2.2	0	1.5	2	0.8	1.5	1.5	0.7	2.2
6	0.5	1	3	1	1.5	0	1.4	2.2	0.5	1	3	1
7	1	2	1.5	0.3	2	1.4	0	2.5	1	2	1.5	0.3
8	0.6	1.8	1.6	2	0.8	2.2	2.5	0	0.6	1.8	1.6	2
9	1.5	1.5	2	2.2	1.5	0.5	1	0.6	0	1.5	1.5	2
10	0.5	1.6	0.7	1	1.5	1	2	1.8	1.5	0	0.5	1.6
11	1.4	1.5	3	0.3	0.7	3	1.5	1.6	1.5	0.5	0	1.4
12	1.5	1	1.5	1.5	2.2	1	0.3	2	2	1.6	1.4	0

Appendix 2

Tables 16, 17, 18, 19, 20, 21, 22, 23 and 24 gives the assignment of twelve facilities ($N = 12$) for five time periods ($T = 5$) for nine efficient layouts obtained from Step 2 (Identify efficient SDFLP layouts using DEA) on which the MADM techniques were applied for ranking. The layout is represented as a 2-D matrix where row is the time period and the column is the location, and each cell is the machine number i.e. the machine ‘i’ placed at the location ‘l’ for the time period ‘t’.

Table 16 Layout 1

Location	1	2	3	4	5	6	7	8	9	10	11	12
<i>Period</i>												
1	1	12	4	7	2	6	5	3	10	9	11	8
2	5	9	11	8	12	1	6	7	2	4	10	3
3	12	11	10	3	9	5	6	2	7	4	8	1
4	5	9	4	2	7	6	12	8	1	11	10	3
5	6	7	4	2	10	3	5	9	11	8	1	12

Table 17 Layout 2

Location	1	2	3	4	5	6	7	8	9	10	11	12
<i>Period</i>												
1	6	2	7	4	3	10	11	9	5	8	1	12
2	8	12	1	5	7	6	2	4	9	3	10	11
3	8	12	1	2	6	7	4	5	9	3	10	11
4	12	8	1	4	2	7	6	11	10	3	9	5
5	12	8	1	11	9	5	3	10	2	4	7	6

Table 18 Layout 4

Location	1	2	3	4	5	6	7	8	9	10	11	12
<i>Period</i>												
1	11	10	4	7	2	6	12	1	8	5	3	9
2	8	6	2	7	4	5	9	3	10	11	1	12
3	7	2	6	8	12	1	5	9	3	10	11	4
4	6	7	2	4	3	10	11	9	5	12	8	1
5	5	9	11	12	8	1	6	7	2	4	10	3

Table 19 Layout 5

Location	1	2	3	4	5	6	7	8	9	10	11	12
<i>Period</i>												
1	5	3	10	9	4	7	6	2	11	8	1	12
2	1	11	10	3	9	5	6	7	2	4	8	12
3	9	3	10	12	8	1	6	7	2	4	11	5
4	5	1	8	12	6	7	4	2	11	10	3	9
5	11	1	8	12	7	6	2	4	10	3	9	5

Table 20 Layout 7

Location	1	2	3	4	5	6	7	8	9	10	11	12
<i>Period</i>												
1	2	6	5	3	10	9	11	12	1	8	7	4
2	2	6	5	8	12	1	11	10	3	9	7	4
3	1	5	9	3	10	11	6	2	7	4	8	12
4	1	8	12	11	10	3	5	9	2	4	7	6
5	1	8	12	11	10	3	5	9	2	4	7	6

Table 21 Layout 14

Location	1	2	3	4	5	6	7	8	9	10	11	12
<i>Period</i>												
1	12	1	8	11	2	6	7	4	9	10	3	5
2	12	1	6	2	7	4	11	10	3	9	5	8
3	12	1	6	2	7	4	11	10	3	9	5	8
4	6	7	2	4	3	10	11	9	5	8	1	12
5	8	1	10	3	4	2	6	7	5	9	11	12

Table 22 Layout 20

Location	1	2	3	4	5	6	7	8	9	10	11	12
<i>Period</i>												
1	12	1	4	7	2	6	11	9	10	3	5	8
2	12	1	4	7	2	6	5	9	3	10	11	8
3	8	1	12	4	7	2	6	5	3	9	10	11
4	8	1	4	2	7	6	5	9	3	10	11	12
5	8	1	4	2	7	6	5	9	3	10	11	12

Table 23 Layout 23

Location	1	2	3	4	5	6	7	8	9	10	11	12
<i>Period</i>												
1	8	1	12	11	10	9	5	3	4	7	2	6
2	9	3	5	12	1	8	6	2	7	4	10	11
3	5	9	3	10	11	1	8	12	2	4	7	6
4	6	7	4	2	10	3	5	9	11	12	8	1
5	1	8	12	11	2	4	7	6	10	3	9	5

Table 24 Layout 29

Location	1	2	3	4	5	6	7	8	9	10	11	12
<i>Period</i>												
1	5	3	10	9	7	4	2	6	11	8	1	12
2	6	2	7	4	3	10	11	9	5	1	8	12
3	6	2	7	4	3	10	11	9	5	8	12	1
4	7	6	2	4	3	10	11	9	5	12	8	1
5	5	9	2	4	7	6	12	1	8	11	10	3

References

Akash, T., & Singh, S. P. (2016). Integrating big data analytic and hybrid firefly-chaotic simulated annealing approach for facility layout problem. *Annals of Operations Research*. doi:10.1007/s10479-016-2237-x.

Albert, E. F. M., Manuel, I., Silvano, M., Marcos, J., & Negreiros, G. (2010). Models and algorithms for fair layout optimization problems. *Annals of Operations Research*, 179, 5–14.

Balakrishnan, J., & Cheng, C. H. (2007). Multi period planning and uncertainty issues in cellular manufacturing: A review and future directions. *European Journal of Operation Research*, 177, 281–309.

Balakrishnan, J., & Cheng, C. H. (2009). The dynamic plant layout problem: Incorporating rolling horizons and forecast uncertainty. *Omega*, 37(1), 165–177.

Balakrishnan, J., Jacobs, F. R., & Venkataramanan, M. A. (1992). Solution for the constrained dynamic facility layout problem. *European Journal of Operation Research*, 57, 280–286.

Bayraktar, E., Jothishankar, M. C., Tatoglu, E., & Wu, T. (2007). Evolution of operations management: Past, present and future. *Management Research News*, 30(11), 843–871.

Beck, M. P., & Lin, B. W. (1983). Some heuristics for the consensus ranking problem. *Computers and Operations Research*, 10(1), 1–7.

Borda, J. C., (1781). M’emoire sur les ’elections au scrutiny. Histoire de l’Acad’emie Royale des Sciences, Ann’ee MDCCLXXXI, Paris, France.

- Bruglia, M., Zanoni, S., & Zavanella, L. (2004). Layout design in dynamic environments: Analytical issues. *International Transition in Operation Research*, 12, 1–19.
- Bruglia, M., Zanoni, S., & Zavanella, L. (2005). Robust versus stable environments. *Production Planning and Control*, 16(1), 71–80.
- Canen, A. G., & Williamson, G. H. (1998). Facility layout overview: Towards competitive advantage. *Facilities*, 16(7/8), 198–203.
- Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research*, 2, 429–444.
- Cook, W. D., & Kress, M. (1985). Ordinal ranking with intensity of preference. *Management Science*, 31(1), 26–32.
- Cook, W. D., & Seiford, L. M. (1982). On the Borda–Kendall consensus method for priority ranking problems. *Management Science*, 28(6), 621–637.
- Date, K., Makked, S., & Nagi, R. (2014). Dominance rules for the optimal placement of a finite-size facility in an existing layout. *Computers and Operations Research*, 51, 182–189.
- Drake, D. F., & Spinler, S. (2013). OM forum-sustainable operations management: An enduring stream or a passing fancy? *Manufacturing and Service Operations Management*, 15(4), 689–700.
- Dubey, R., Gunasekaran, A., & Childe, S. J. (2015). The design of a responsive sustainable supply chain network under uncertainty. *The International Journal of Advanced Manufacturing Technology*, 80(1–4), 427–445.
- Dutta, K. N., & Sahu, S. (1982). A multi goal heuristic for facilities design problem: Mughal. *International Journal of Production Research*, 20, 147–154.
- Elliott, B. (2001). Operations management: A key player in achieving a sustainable future. *Management Services*, 45(7), 14–19.
- Ertay, T., Ruan, D., & Tuzkaya, U. R. (2006). Integrating data envelopment analysis and analytic hierarchy for the facility layout design in manufacturing systems. *Information Sciences*, 176, 237–262.
- Fortenberry, J. C., & Cox, J. F. (1985). Multiple criteria approach to the facilities layout problem. *International Journal of Production Research*, 23, 773–782.
- Garcia-Hernandez, L., et al. (2013). Recycling plants layout design by means of an interactive genetic algorithm. *Intelligent Automation and Soft Computing*, 19(3), 457–468.
- García-Hernández, L., et al. (2015). Facility layout design using a multi-objective interactive genetic algorithm to support the DM. *Expert Systems*, 32(1), 94–107.
- Govindan, K., & Cheng, T. C. E. (2015). Sustainable supply chain management: Advances in operations research perspective. *Computers and Operations Research*, 54, 177–179.
- Gupta, M. C. (1995). Environmental management and its impact on the operations function. *International Journal of Operations and Production Management*, 15(8), 34–51.
- Gupta, M., & Sharma, K. (1996). Environmental operations management: An opportunity for improvement. *Production and Inventory Management Journal*, 37(3), 40–46.
- Hajek, B. (1988). Cooling schedules for optimal annealing. *Mathematics of Operations Research*, 3, 311–329.
- Hwang, C. L., & Yoon, K. P. (1981). *Multiple attribute decision making: Methods and applications*. New York: Springer.
- Kaur, H., Singh, S. P., & Glardon, R. (2017). An integer linear program for integrated supplier selection: A sustainable flexible framework. *Global Journal of Flexible Systems Management*, 17(2), 113–134.
- Kendall, M. (1962). *Rank correlation methods* (3rd ed.). New York: Hafner.
- Khare, V. K., Khare, M. K., & Neema, M. L. (1988a). Estimation of distribution parameters associated with facilities design problem involving forward and backtracking of materials. *Computers and Industrial Engineering*, 14, 63–75.
- Khare, V. K., Khare, M. K., & Neema, M. L. (1988b). Combined computer-aided approach for the facilities design problem and estimation of the distribution parameter in the case of multi goal optimization. *Computers and Industrial Engineering*, 14, 465–476.
- Kia, R., Baboli, A., Javadian, N., Tavakkoli-Moghaddam, R., Kazemi, M., & Khorrami, J. (2012). Solving a group layout design model of a dynamic cellular manufacturing system with alternative process routings, lot splitting and flexible reconfiguration by simulated annealing. *Computers and Operations Research*, 39(11), 2642–2658.
- Kirkpatrick, S., Gelatt, C. D, Jr., & Vecchi, M. P. (1983). Optimization by simulated annealing. *Science*, 220, 671–677.
- Kleindorfer, P. R., & Kunreuther, H. C. (1994). Siting of hazardous facilities. *Handbooks in operations research and management science*, 6, 403–440.
- Kleindorfer, P. R., Singhal, K., & Wassenhove, L. N. V. (2005). Sustainable operations management. *Production and Operations Management*, 14(4), 482–492.

- Koopmans, T. C. S., & Beckman, M. (1957). Assignment problem and the location of economic activities. *Econometric*, 25, 53–76.
- Kulturel-Konak, S. (2007). Approaches to uncertainties in facility layout problem: Perspectives at the beginning of the 21st century. *Journal of Intelligent Manufacturing*, 14(2), 219–228.
- Kulturel-Konak, S., Smith, A. E., & Norman, B. A. (2004). Layout optimization considering production uncertainty and routing flexibility. *International Journal of Production Research*, 42(21), 4475–4493.
- Kusiak, A., & Heragu, S. S. (1987). The facility layout problem. *European Journal of operational research*, 29(3), 229–251.
- Lieckens, K. T., Colen, P. J., & Lambrecht, M. R. (2015). Network and contract optimization for maintenance services with remanufacturing. *Computers and Operations Research*, 54, 232–244.
- Linton, J. D., Klassen, R., & Jayaraman, V. (2007). Sustainable supply chains: An introduction. *Journal of Operations Management*, 25(6), 1075–1082.
- Les, R. F., & Fariborz, Y. P. (1998). Integrating the analytic hierarchy process and graph theory to model facilities layout. *Annals of Operations Research*, 82, 435–451.
- Malakooti, B. (1989). Multiple objective facility layout: A heuristic to generate efficient alternatives. *International Journal of Production Research*, 27(7), 1225–1238.
- Matai, R. (2015). Solving multi objective facility layout problem using modified simulated annealing. *Applied Mathematics and Computation*, 261, 302–311.
- Matai, R., Singh, S. P., & Mittal, M. L. (2013a). A non-greedy systematic neighbourhood search heuristic for solving facility layout problem. *International Journal of Advanced Manufacturing Technology*, 68, 1665–1675.
- Matai, R., Singh, S. P., & Mittal, M. L. (2013b). Modified simulated annealing based approach for multi objective facility layout problem. *International Journal of Production Research*, 51(14), 4273–4288.
- Matai, R., Singh, S. P., & Mittal, M. L. (2013c). A new heuristic for solving facility layout problem. *International Journal of Advance Operations Management*, 5(2), 137–158.
- McKendall, A. R., Shang, J., & Kuppusamy, S. (2006). Simulated annealing heuristics for the dynamic facility layout problem. *Computers and Operations Research*, 33(8), 2431–2444.
- Moslemipour, G., & Lee, T. S. (2011). Intelligent design of a dynamic machine layout in uncertain environment of flexible manufacturing systems. *Journal of Intelligent Manufacturing*, 23(5), 1849–1860.
- Moslemipour, G., Lee, T. S., & Rilling, D. (2012). A review of intelligent approaches for designing dynamic and robust layout in flexible manufacturing systems. *The International Journal of Advanced Manufacturing Technology*, 60(1–4), 11–27.
- Nunes, B., & Bennett, D. (2010). Green operations initiatives in the automotive industry: An environmental reports analysis and benchmarking study. *Benchmarking: An International Journal*, 17(3), 396–420.
- O'brien, C., & Abdel Barr, S. E. Z. (1980). An interactive approach to computer aided facility layout. *International Journal of Production Research*, 18(2), 201–211.
- Rosenblatt, M. J. (1979). The facilities layout problem: A multi goal approach. *International Journal of Production Research*, 17, 323–332.
- Rosenblatt, M. J., & Kropp, D. H. (1992). The single period stochastic plan layout problem. *IIE Transactions*, 24(2), 169–176.
- Rosenblatt, M. J., & Lee, H. L. (1987). A robustness approach to facilities design. *International journal of production research*, 25(4), 479–486.
- Saaty, T. L. (1980). *The analytic hierarchy process*. New York: McGraw-Hill.
- Sacaluga, A. M. M., & Froján, J. E. P. (2014). Best practices in sustainable supply chain management: A literature review. In C. Hernandez Iglesias & J. M. Perez Rios (Eds.), *Managing complexity* (pp. 209–216). Valladolid: University of Valladolid.
- Sarkis, J. (2001). Introduction. *Greener manufacturing and operations: From design to delivery and back* (pp. 15–21). Sheffield: Greenleaf Publishing.
- Singh, S. P., & Sharma, R. R. K. (2006). A review of different approaches to the facility layout problem. *The International Journal of Advanced Manufacturing Technology*, 30(5–6), 425–433.
- Sinuanay-Stern, Z., Mehrez, A., & Hadad, Y. (2000). An AHP/DEA methodology for ranking decision making units. *International Transactions in Operational Research*, 7, 109–124.
- Subramoniam, R., Huisingh, D., & Chinnam, R. B. (2009). Remanufacturing for the automotive aftermarket—strategic factors: Literature review and future research needs. *Journal of Cleaner Production*, 17(13), 1163–1174.
- Sushil, (2009). Interpretive ranking process. *Global Journal of Flexible Systems Management*, 10(4), 1–10.
- Tavana, M., LoPinto, F., & Smither, J. W., (2007). A hybrid distance—based ideal—seeking consensus ranking model. *Journal of applied Mathematics and Decision Sciences*, Article ID 20489, p. 18.
- Tayal, A., & Singh, S. P. (2014). Chaotic simulated annealing for solving stochastic dynamic facility layout problem. *Journal of International Management Studies*, 14(2), 67–74.

- Tayal, A., & Singh, S. P. (2015). Integrated SA–DEA–TOPSIS based solution approach for multi objective stochastic dynamic facility layout problem. *International Journal of Business and Systems Research*.
- Tayal, A., & Singh, S. P. (2016a). Analysis of simulated annealing cooling schemas for design of optimal flexible layout under uncertain dynamic product demand. *International Journal of Operation Research*.
- Tayal, A., & Singh, S. P. (2016b). Flexible layout design for uncertain product demand by integrating firefly and chaotic simulated annealing approach. *Global Journal of Flexible Systems Management*.
- Tayal, A., & Singh, S. P. (2016c). Analyzing the effect of chaos functions in solving stochastic dynamic facility layout problem using CSA. In *Advanced computing and communication technologies* (pp. 99–108). Singapore: Springer.
- Timothy, L. U. (1998). Solution procedures for the dynamic facility layout problem. *Annals of Operations Research*, 76, 323–342.
- Tompkins, J. A., White, J. A., Bozer, Y. A., Frazelle, E. H., Tanchoco, J. M. A., & Trevino, J. (1996). *Facilities planning* (2nd ed., pp. 36–47). Wiley.
- Tompkins, J. A., White, J. A., Bozer, Y. A., & Tanchoco, J. M. A. (2003). *Facilities planning*. Wiley.
- Yang, L., Deuse, J., & Jiang, P. (2013). Multiple-attribute decision-making approach for an energy-efficient facility layout design. *The International Journal of Advanced Manufacturing Technology*, 66(5), 795–807.
- Yang, T., & Hung, C. C. (2007). Multiple-attribute decision making methods for plant layout design problem. *Robot Computer-Integrated Manufacturing*, 23, 126–137.
- Yang, T., & Kuo, C. (2003). A hierarchical AHP/DEA methodology for the facilities layout design problem. *European Journal Operation Research*, 147, 128–136.
- Yu, W., & Ramanathan, R. (2015). An empirical examination of stakeholder pressures, green operations practices and environmental performance. *International Journal of Production Research*, 1–18 (ahead-of-print). doi:[10.1080/00207543.2014.931608](https://doi.org/10.1080/00207543.2014.931608).
- Zouein, P. P., & Tommelein, I. D. (1999). Dynamic layout planning using a hybrid incremental solution method. *Journal of construction engineering and management*, 125(6), 400–408.