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FORMULATING AND SOLVING SUSTAINABLE STOCHASTIC DYNAMIC FACILITY LAYOUT PROBLEM: A KEY TO SUSTAINABLE OPERATIONS

--Manuscript Draft--

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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 is then analyzed by Data Envelopment Analysis (DEA) to identify efficient layouts. A novel hierarchical methodology of consensus ranking of layouts is proposed which combines the multiple attributes/criteria. Multi Attribute decision-making (MADM) Techniques such as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Interpretive Ranking Process (IRP) and Analytic hierarchy process (AHP), 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.

Authors’ Reply to Reviewers’ Comments

We are grateful to the reviewers for their insightful observations which have significantly improved our manuscript. We hope that the revised version of the paper addresses all issues and queries raised by the reviewers, and our responses to both the reviewers’ comments are provided below.

Authors’ reply to Reviewer # 1

Overall comment*:*

This paper proposes a methodology to solve the SDFLP from a sustainable perspective. The methodology is mainly composed of generating alternative layouts for FLP by SA and CSA, identifying efficient layouts by EDA, and ranking the layouts based on the AHP, the TOPSIS and the Consensus Ranked method. However, there exist many shortcomings that impede the acceptance of the paper

Response:

We are thankful to the reviewer for the insightful comment. We have strictly followed the suggestions to remove the shortcomings from the revised paper and have incorporated all the suggestions/comments raised by the reviewer # 1 in the revised manuscript. The detailed responses for each comment are provided below.

Comment # 1: *All the applied methods have been widely used in the workshop facility layout planning. The authors claim to solve the FLP from a sustainable perspective; however, a simple integration of all the methods is not enough. The generation of layouts is the most crucial part for obtaining a sustainable layout for the facility layout problem. As far as I know, much practical constraints can be converted into the "objective functions" or "constraints" when establishing mathematical NP-hard models and applying meta-heuristics to obtain the alternative layouts. If the authors can add more restrictions in the first step, the complexity of the following steps will be greatly reduced.*

Response:

We agree with the reviewer. In the revised paper, we have explicitly provided the classification of the criteria considered to make the facility layout planning a sustainable. Planet (environmental) and people (social) aspect of sustainability is incorporated through considering these qualitative factors. However, the mathematical model (SDFLP) shown in the paper take cares of the profit (economy) aspect of the sustainability by considering quantitative parameters. The sustainability issue is shown in figure 1 and figure 2 in the revised manuscript and is reproduced below for ready reference. The flow chart of the sustainable SDFLP is shown in figure 3.

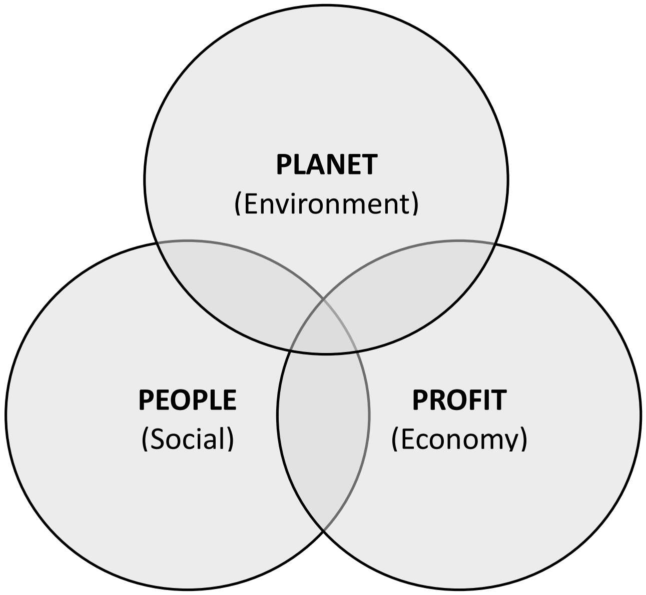

Fig 1 3-Ps of Sustainability

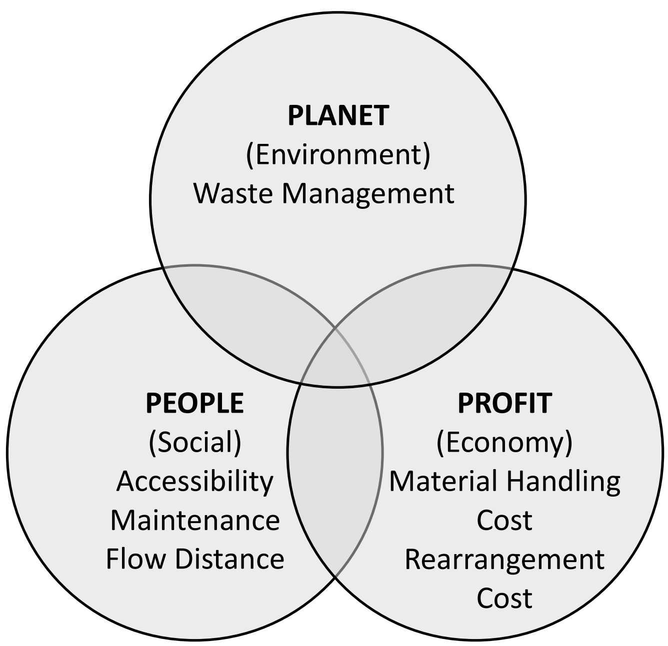

Fig 2 *3-P's framework of Sustainable SDFLP*

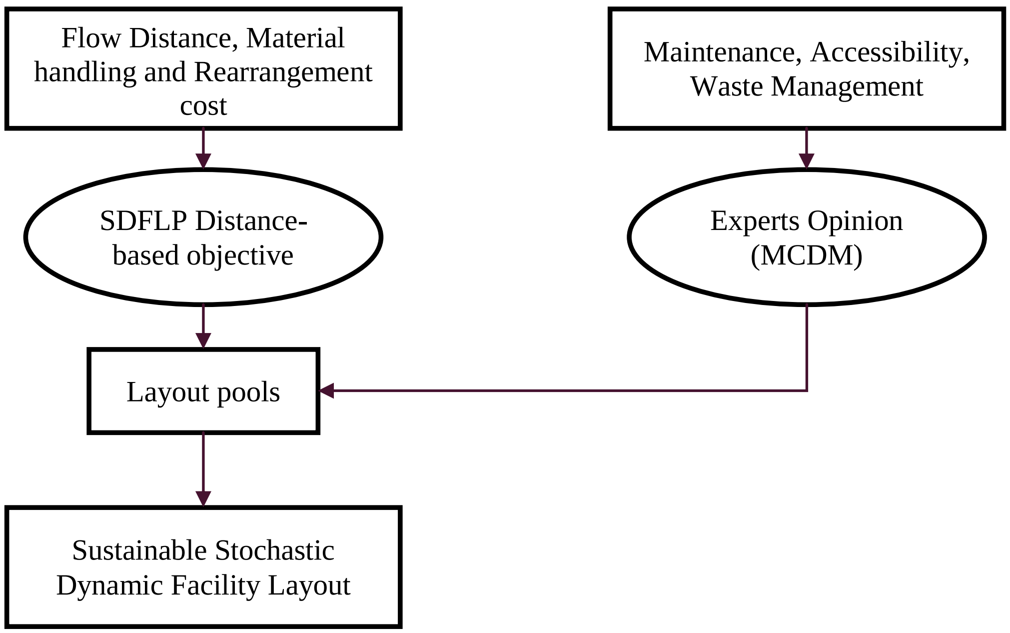

Fig. 3 *Flow chart of SSDFLP*

Comments # 2: *There are many extant literatures on the FLP and the authors claimed that they are solving the FLP in the sustainable aspects. However, the analysis is not so convincing and much more discussions are required to demonstrate the sustainability of the proposed methodology.*

Response:

We are thankful to the reviewer for this comment. In the revised paper, we have added paragraphs under section 1 (Introduction) and section 3.2 (Quantitative and Qualitative Factors for Sustainability) and section 3.3 (Sustainable SDFLP Formulation) to demonstrate the sustainability of the proposed methodology. Finally, the discussion of the paper has been enriched in order to show our contribution more explicitly.

> **"Introduction**
> In this paper we present a novel method to solve sustainable SDFLP considering both qualitative and quantitative factors under stochastic product demand flow over multi time period, using hierarchical framework of - meta heuristic, Multiple Criteria Decision Making (MCDM) techniques and Consensus Ranking method. This methodology integrates meta heuristics (SA, CSA, Hybrid FA/CSA), DEA (to get efficient layouts), TOPSIS, IRP and AHP (for MCDM) and aggregate

ranking methods (Borda-Kendall and Integer Linear Programming (ILP)) for six criteria i.e. MHC, flow distance, rearrangement cost, accessibility, maintenance and waste management.

3.2. Quantitative and Qualitative Factors for Sustainability

A preliminary study of literature and experts opinion was done to determine the quantitative and qualitative design attributes. The quantitative attributes included material handling cost, flow distance and the rearrangement cost, and qualitative attributes are, accessibility, maintenance and waste management. In terms of sustainable operations for the facility layout MHC, R_c, flow distance, are the economic pillars while maintenance and accessibility are the social pillars and waste management corresponds to environmental pillar.

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 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.

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.

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 FLP involves assigning facilities to location to satisfy the multiple quantitative and qualitative parameters. For a sustainable facility layout design problem in a stochastic demand, we would like to minimize MHC, R_c, flow distance and waste, and maximize accessibility and maintenance. Figure 3 gives this diagrammatic representation of the Sustainable Stochastic Dynamic Facility Layout Model."

Comment # 3: *The authors applied an aggregated ranking method to rank the ultimatum layouts. They needed to make more comparisons to show its advantages*.

Response:

We are once again thankful to the reviewer for this insightful comment. In the revised paper, we have added one section on "Integer Linear Programming method" to generate aggregate ranking other than "BAK".

Comment # 4: *The authors used the AHP to calculate the weights of quantitative and qualitative criteria, and no improvements are made to the basic AHP. In fact, when using the AHP to generate the weights, the subjective uncertainties from the invited experts have a crucial impact on the results. Thus, uncertainties and the robustness of applying the AHP should be considered*.

Response:

We are once again thankful to the reviewer for this comment. In order to take in to account the uncertainties from the invited experts, another ranking method has been included Interpretive Ranking Process (IRP).

Comment # 5: *There are many grammar errors and confusing sentences. Major revisions and polishements are required.*

For example, the sentence "Traditionally, it solved using ....." on Line 30, Page 1.

Lines 48-50, Page 5

Lines 36-41, Page 6

Line 46, Page 9

The authors need to revised the paper totally to avoid much mistakes and awkward sentences

Response:

We are once again thankful to the reviewer for mentioning these corrections. We have incorporated all corrections mentioned by the reviewer and proof read the whole paper to remove possible grammatical errors and unclear phrases to make the paper easy for understanding.

Comment # 6: *There are many format mistakes in the paper, for example, Titles for Figure 2, Figure 3, Figure 4 and the title for the Step 2 of the methodology. Obviously, the authors didn't check before approving their submissions.*

Response:

We are once again thankful to the reviewer for this comment. Authors have carefully made the necessary correction as cited by the reviewers and tried their best to keep consistency in the formatting of the paper.

Authors’ reply to Reviewer # 2

Overall comment:

This paper proposes a novel method to solve FLP considering both qualitative and quantitative factors under stochastic product demand flow over multi time period. This looks interesting but argues for justifying this novel approach are weak. Please, authors must incorporated new argues that highlight the novelty and importance of their contribution

Response:

We are really thankful to the reviewer for encouraging words. We have incorporated all suggestions/comments raised by the reviewer # 2 in the revised manuscript. The detailed responses for each comment are provided below.

Comment # 1: *In this work, they consider both qualitative and quantitative factors in FLP. However, there are some existing works that considered both aspects and they are not referenced in this paper. For example:*

Garcia-Hernandez, Laura, et al. (2013), "Recycling Plants Layout Design by Means of an Interactive Genetic Algorithm." Intelligent Automation & Soft Computing19.3 457-468.

García-Hernández, Laura, et al. (2015) “Facility layout design using a multi-objective interactive genetic algorithm to support the DM." Expert Systems 32.1, 94-107

Response:

We agree with the reviewer’s comment on this. Some more recent and existing published work in FLP considering both qualitative and quantitative factors have been included both in literature review and references for better visibility and understanding of the research.

Comment # 2: *Methodology section should be revised in depth and explained better because sometimes is difficult to understand correctly.*

Response:

We are thankful for this comment. In the revised manuscript, we have improved the Methodology section. The section 4 (Methodology to Solve Sustainable SDFLP) has been extended and the newly added paragraphs are shown in the red text in the revised manuscript.

Comment # 3: Conclusions section is very short and should be extended.

Response:

We are thankful to the reviewer and the conclusion as suggested has been extended. The revised conclusion section is reproduced below.

> "**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."

Comment # 4: *There is a format mistake in pages 11-14. Please, correct it.*

Response:

We are once again thankful to the reviewer for this comment. We have carefully made the necessary correction as cited by the reviewers and tried their best to keep consistency in the formatting of the paper.

Comment # 4: *Additionally, the bibliography should be updated, there are only few references in the last 5 years*

Response:

We are thankful for this comment. In the revised manuscript, we have added few more recent publications in the references to provide up-to-date state of the art.

FORMULATING AND SOLVING SUSTAINABLE STOCHASTIC DYNAMIC FACILITY LAYOUT PROBLEM: A KEY TO SUSTAINABLE OPERATIONS

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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 (DEA) to identify efficient layouts. A novel hierarchical methodology of consensus ranking of layouts is proposed which combines the multiple attributes/criteria. Multi Attribute decision-making (MADM) Techniques such as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Interpretive Ranking Process (IRP) and Analytic hierarchy process (AHP), 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 Kunreuther and Kleindorfer (1980) 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 Figure 1.

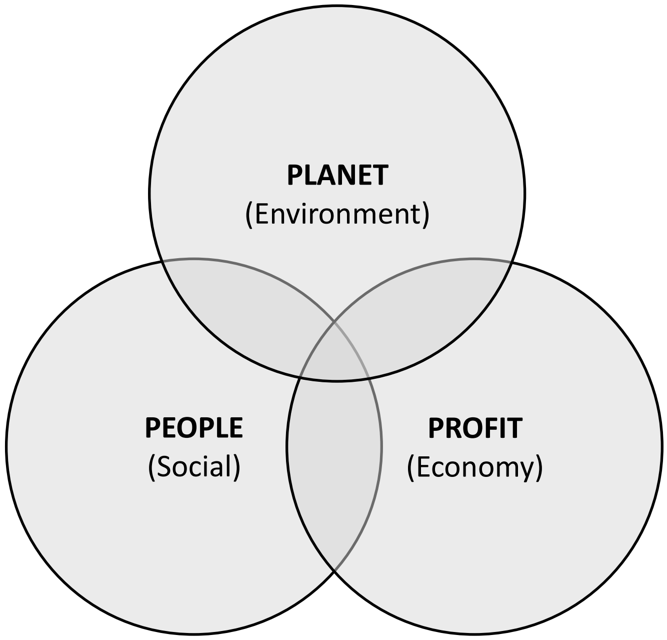

Fig. 1 3-Ps of Sustainability

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 Figure 2.

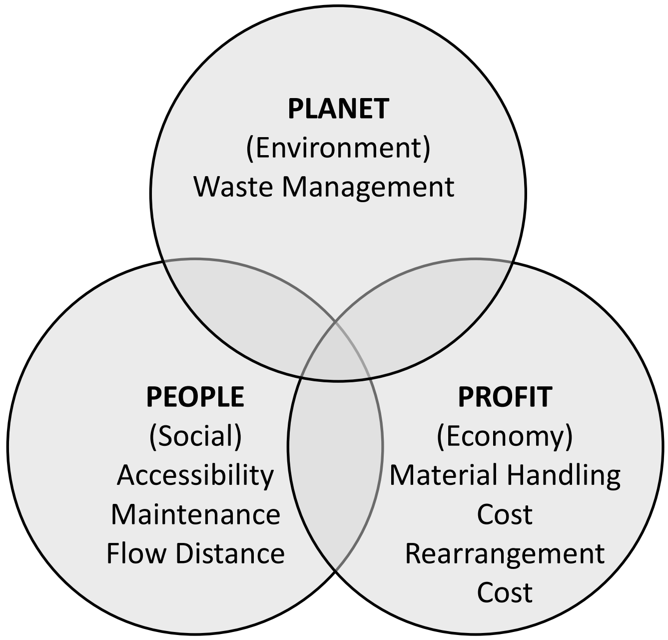

Fig. 2 3-P's framework of Sustainable SDFLP

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 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 et al., 2013; 2015; Yang et al., 2013; Tayal and Singh, 2014a).

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 section 7 summarizes our research findings.

2. LITERATURE REVIEW

2.1 Sustainable Operations Management

Elliot (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-Barr, 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, 2014a) 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 on facility layout can be seen from

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 Koopman and Beckman (1957), given in Equations (1)-(4). Balakrishnan et al. (1992) provided the QAP mathematical model for Dynamic Facility Layout Problem (DFLP), including the rearrangement cost, is given in Equations (5) - (9).

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
Zp	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
$\sigma_{ij}^2.$	Variance of product demand

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

Subject to:

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

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

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

Dynamic FLP is modeled as shown below:

$$Minimize\,\mathrm{C}(\pi) = \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{M} \sum_{l=1}^{M} \sum_{q=1}^{M} f_{tij} \mathrm{d}_{lq} x_{til} x_{tjq} + \sum_{t=2}^{T} \sum_{i=1}^{M} \sum_{l=1}^{M} \sum_{q=1}^{M} \mathrm{a}_{tilq} \mathrm{y}_{tilq} \tag{5}$$

Subject to:

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

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

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

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

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 Equation (10) (Moslemipour and Lee, 2011).

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

Subject to:

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

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

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

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

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.

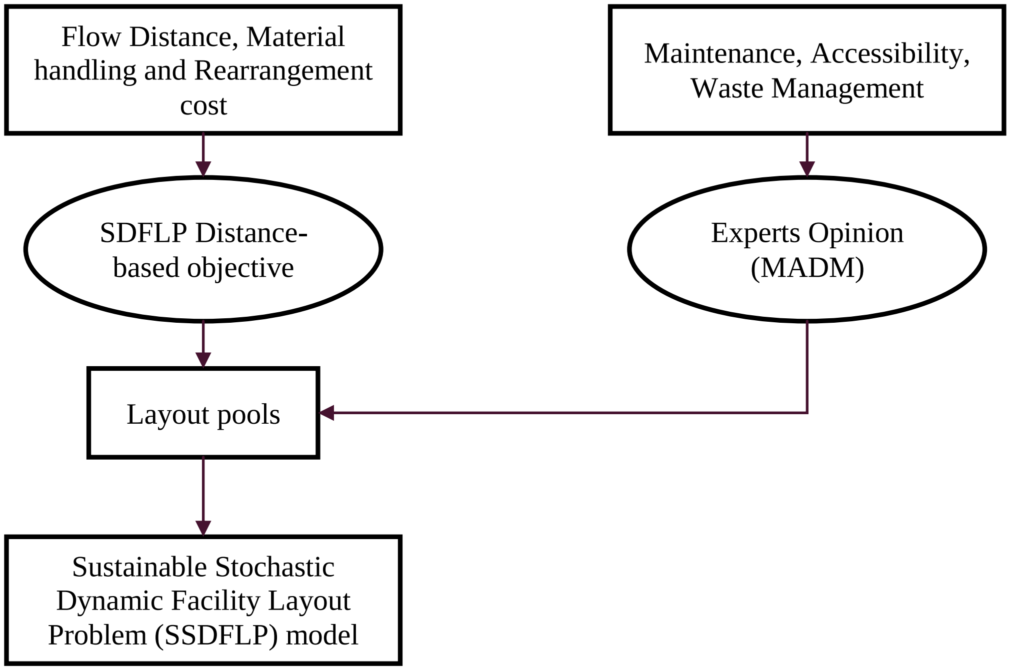

Fig. 3 Flow chart of SSDFLP

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 3 Ps 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 is presented in Figure 4. The detailed description of each step is provided in the following paragraphs.

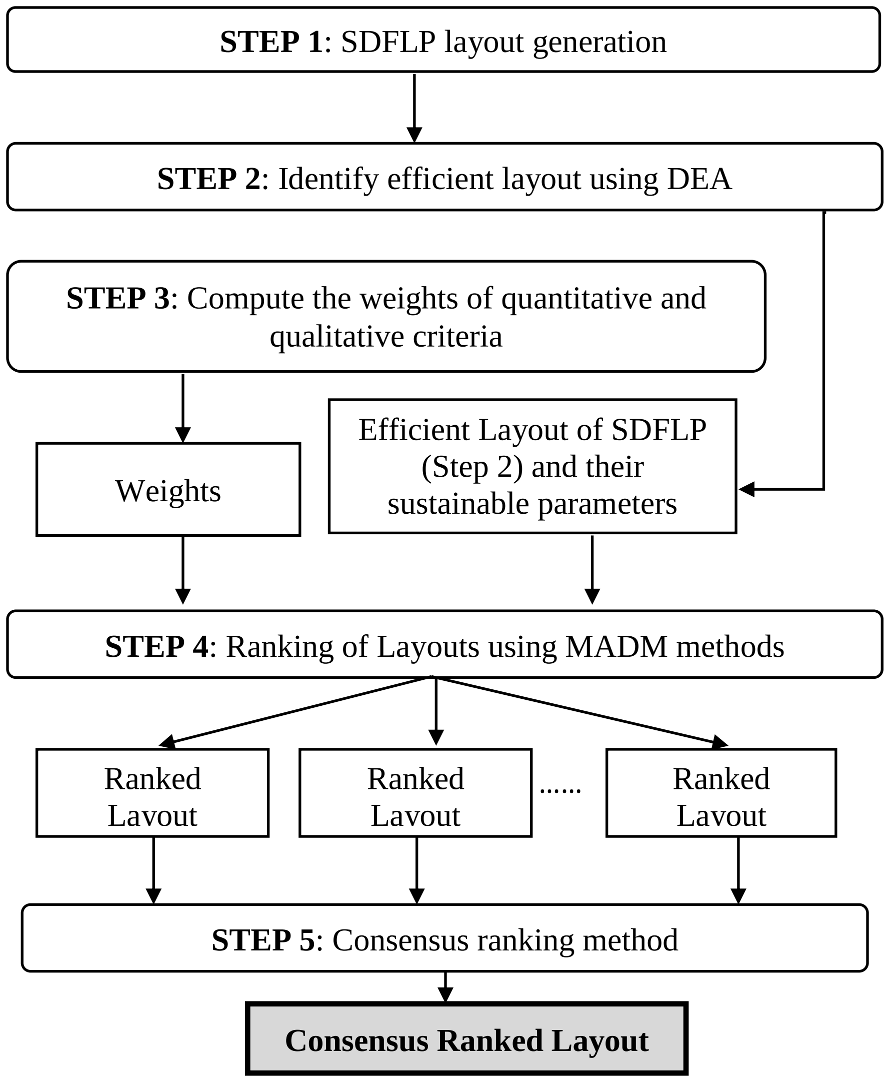

Fig. 4 Methodological framework of proposed SSDFLP

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 Figure 5, Figure 6, and Figure 7, respectively. Detailed description on meta-heuristic techniques for solving SDFLP can be found in Tayal and Singh (2015; 2016; 2016a).

Initialize

Start with a known or randomly generated initial solution, s_0 and assign $s=s_0$

Initialize the temperature T_0

Generate new neighborhood solution, s'

Compute the neighborhood position value for the facility by exchanging two facilities (both are generated randomly)

Using above position vectors, s' is computed

Start Inner loop

Compute the OFV i.e. f(s) for s_0 and s'

Compute the OFV given in Equation (10), subject to conditions Equation (11)-(14) for s_0 and s'

Check

if $f(s) > f(s')$, assign $s = s'$

else if $P((f(s')-f(s))/KT) < rand$, assign $s = s'$

Repeat until inner loop criteria

Decrease the temperature, using **cooling schedule function**

Repeat until stopping criteria, reset inner loop criteria

Output the best solution's' it's material handling cost, rearrangement cost, and flow distance

Fig. 5 Simulated Annealing for solving SDFLP

Initialize

Start with a known or randomly generated initial solution, s0 and assign s=s0

Generate the different chaotic variables, $H_{k_i}, i = 1, 2, \ldots, N$ by using the chaotic systems,

$$H_{k+1} = f(\mu, H_k) = \mu H_k(1 - H_k) \quad \text{(a)}$$

where, $H_k \in [0,1]$. H_k is the value of the variable H at the k^{th} iteration, k is a random integer in set {1, …, 400} and μ is called the bifurcation parameter of the system, in this paper μ is considered as 4.

Initialize the temperature T_0

Generate new neighborhood solution, s'

Compute the initial position value for the facility,

$$p_{0,i} = a_i + (b_i - a_i) \times H_{k_i} \quad \text{(b)}$$

where, a_i is the lower limit of the facility position and b_i is the upper limit of the facility position.

Compute the neighborhood position value for the facility, using

$$y_{m,i} = p_{m,i} + \alpha \times (b_i - a_i) \times H_{k_m} \quad \text{(c)}$$

where, i is randomly chosen from the set {1,2, …, N}, H_{k_m} is a chaotic variable produced by Equation (a), and k_m is a random integer in the set {1, …, 400}

Here, α is a variable which is decreased by the formula $\alpha = \alpha \times e^{-\beta}$ in each iteration. In this paper β is taken as 1.01

Using above position vectors, s' is computed

Start Inner loop

Compute the OFV i.e. f(s) for s0 and s'

Compute OFV given in Equation (10), subject to conditions Equation (11)-(14) for s0 and s'

Check,

if f(s) > f(s'), assign s = s'

else if P((f(s')-f(s))/KT) < rand, assign s = s'

Repeat until inner loop criteria

Fig. 6 Chaotic simulated annealing for solving SDFLP

Initialization Parameters

numFF = 5 | H_k = 0.09, μ = 4.0, α_{csa} = 1.0, β_{csa} = 1.01,

MaxGeneration = 2000 | T^0 = 10.0, Minimum Temperature = 0.01,

Firefly attractiveness at r = 0, β_0 = 1, | Inner loop criteria = 10

Stage 1:

Initialization for FA

  Initialize the population of the fireflies s_p *(p=1, 2, 3…numFF)*
  Each firefly position represents a solution in the search space, $s = [s_1, s_2, \dots, s_p, \dots, s_{numFF}]^T$
  Find the firefly light intensity, I_p at s_p
  Define the light absorption coefficient, γ

Firefly Algorithm

  while (z < *MaxGeneration*)
    for p = *1 : number of fireflies*
      for m = *1 : number of fireflies*
        if ($I_m > I_p$)
        Move firefly 'p' towards firefly 'm', using Equation (18)
        Evaluate new solution of firefly 'p' using Equation (15), update I_p using Equation (17)
        end if
        Vary attractiveness with distance r via exp $[-\gamma r]$
      end for m
    end for p
    Rank the fireflies and find the current best
    z=z+1
  end while

Output: The best solution from Firefly Algorithm, *s0*

Stage 2:

Initialization for CSA

  Set initial solution, *s0* and assign *s=s0*
  Generate the chaotic variables using Equation (20)
  Initialize the temperature, T^0

while (T^0 < Minimum Temperature)
  Generate new neighbourhood solution, *s'* using Equation (15)
  Compute the OFV i.e. f(s) for *s* and *s'*
  lp = 0
  while (lp < Inner loop criteria)
    if   *f(s) > f(s')*, assign *s = s'*
    else if   *P((f(s')-f(s))/KT) < rand*, assign *s = s'*
    lp = lp + 1
  end while
  Decrease T^0, using exponential cooling
end while

Output: The best solution 's' of SDFLP using Hybrid FA/CSA approach, its Objective Function Values and CPU time

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

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.

Notations	**Description**
$\mathrm{DMU_k}$	$\mathrm{k^{th}}$ decision making unit (DMU), $\mathrm{k} = 1,2, \dots, \mathrm{n}$
$\mathrm{X_{ik}}$	$\mathrm{i^{th}}$ input for the $\mathrm{k^{th}}$ DMU, $\mathrm{i} = 1,2, \dots, \mathrm{m}$ and $\mathrm{k} = 1,2, \dots, \mathrm{n}$
$\mathrm{Y_{rk}}$	$\mathrm{r^{th}}$ output for the $\mathrm{k^{th}}$ DMU, $\mathrm{r} = 1,2, \dots, \mathrm{s}$ and $\mathrm{k} = 1,2, \dots, \mathrm{n}$
$\mathrm{v_i}$	associated weight for the $\mathrm{i^{th}}$ input, $\mathrm{i} = 1,2, \dots, \mathrm{m}$
$\mathrm{u_r}$	associated weight for the $\mathrm{r^{th}}$ output, $\mathrm{r} = 1,2, \dots, \mathrm{s}$
$\mathrm{h_k}$	efficiency score ($\mathrm{h_k} \leq 1$)

Specifically, $\mathrm{DMU_k}$consumes amount $\mathrm{X_{ik}}$ of input *i* and produces amount $\mathrm{Y_{rk}}$of output *r*, that can be incorporated into an efficiency measure – the weighted sum of the outputs divided by the weighted sum of the inputs $\mathrm{h_k} = \sum \mathrm{u_r Y_{rk}} / \sum \mathrm{v_i X_{ik}}$. This definition requires a set of factor weights $\mathrm{u_r}$and $\mathrm{v_i}$ which are the decision variables. Each $\mathrm{DMU_k}$is assigned the highest possible efficiency score ($\mathrm{h_k} \leq 1$) 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 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 $w_i = r_i/(r_1 + r_2 + \cdots + r_n)$.

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 Equation (15):

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

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 $(\mathrm{A}_1, \mathrm{A}_2, \ldots \mathrm{A}_\mathrm{m})$ and criteria by $(\mathrm{C}_1, \mathrm{C}_2, \ldots \mathrm{C}_\mathrm{n})$. An element x_{ij} of the matrix indicted the performance rating of the i^th alternatives, A_i, with respect to the j^th criteria, C_j, as shown in Equation (16):

$$\mathrm{D} \quad = \quad \begin{array}{c} \\ \mathrm{A}_1 \\ \mathrm{A}_2 \\ \mathrm{A}_3 \\ \vdots \\ \mathrm{A}_\mathrm{m} \end{array} \begin{array}{c} \begin{array}{ccccc} \mathrm{C}_1 & \mathrm{C}_2 & \mathrm{C}_3 & \cdots & \mathrm{C}_\mathrm{n} \end{array} \\ \begin{bmatrix} \mathrm{x}_{11} & \mathrm{x}_{12} & \mathrm{x}_{13} & \cdots & \mathrm{x}_{1\mathrm{n}} \\ \mathrm{x}_{21} & \mathrm{x}_{22} & \mathrm{x}_{23} & \cdots & \mathrm{x}_{2\mathrm{n}} \\ \mathrm{x}_{31} & \mathrm{x}_{32} & \mathrm{x}_{33} & \cdots & \mathrm{x}_{3\mathrm{n}} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathrm{x}_{\mathrm{m}1} & \mathrm{x}_{\mathrm{m}2} & \mathrm{x}_{\mathrm{m}3} & \cdots & \mathrm{x}_{\mathrm{mn}} \end{bmatrix} \end{array} \qquad (16)$$

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 $(\mathrm{C}_\mathrm{j},\ \mathrm{j} = 1,2, \ldots, \mathrm{n})$ 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 $(\mathrm{A}_\mathrm{i},\ \mathrm{i} = 1,2 \ldots \mathrm{m})$. 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. $W = \{w_j \mid j = 1, 2, \dots, n\}$. 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 Equation (17):

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

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

Calculate normalized rating

Normalized ratings are calculated for each element in the decision matrix.

Calculate weighted normalized ratings:

The weighted normalized value v_{ij} is calculated by Equation (a).

$$v_{ij} = w_j r_{ij}, \qquad i = 1, \dots, m; j = 1, \dots, n. \qquad \text{(a)}$$

Identify positive ideal (A^*) and negative ideal (A^-) solutions:

The A^* and A^- are defined in terms of the weighted normalized values, as shown in Equations (b) and (c), respectively:

$$A^* = \{v_1^*, v_2^*, \dots, v_j^*, \dots, v_n^*\} = \left\{\left(\max_i v_{ij} \middle| j \in J_1\right), \left(\min_i v_{ij} \middle| j \in J_2\right) \middle| i = 1, \dots, m\right\} \qquad \text{(b)}$$

$$A^- = \{v_1^-, v_2^-, \dots, v_j^-, \dots, v_n^-\} = \left\{\left(\min_i v_{ij} \middle| j \in J_1\right), \left(\max_i v_{ij} \middle| j \in J_2\right) \middle| i = 1, \dots, m\right\} \qquad \text{(c)}$$

where$J_1$is a set of benefit attributes (larger-the-better type) and $J_2$is a set of cost attributes (smaller-the-better-type).

Calculate separation measures:

The separation (distance) between alternatives is measured by the n-dimensional distance, which could be either Euclidian or Manhattan depending on the value of *p*. The separation of each alternative from the positive ideal solution, A^*, is given by Equation (d):

$$S_i^* = \sqrt[p]{\sum_{j=1}^{n}\left(v_{ij} - v_j^*\right)^p}, \qquad i = 1, \dots, m. \qquad \text{(d)}$$

Similarly, the separation from the negative ideal solution, A^-, is given by Equation (e):

$$S_i^- = \sqrt[p]{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^p}, \qquad i = 1, \dots, m. \qquad \text{(e)}$$

if p=1, then Manhattan distance

if p=2, then Euclidian distance

to compute the separation measures.

Calculate similarities to ideal solution:

This is defined in Equation (f):

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-}, \qquad i = 1, \dots, m. \qquad \text{(f)}$$

Note that $0 \leq C_i^* \leq 1$, where $C_i^* = 0$ when $A_i = A^-$, and $C_i^* = 1$ when $A_i = A^*$.

Finally, rank the alternative with maximum C_i^*.

Fig. 8 Pseudo code of TOPSIS method for ranking 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.

- ***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 Figure 9.

Step 1: Identify two sets of variables - one to be ranked with reference to the other, e.g. Alternatives and Criteria,

Step 2: Clarify the contextual relationship between the alternatives and the criteria.

Step 3: Develop a cross-interaction matrix between the alternatives and criteria.

Step 4: Convert the 2-D matrix into an interpretive matrix.

Step 5: Convert the interpretive matrix into an interpretive logic of pair-wise comparisons and dominating interactions matrix by interpreting the dominance of one interaction over the other.

Step 6: Develop ranking and interpret the ranks in terms of dominance of number of interactions.

Step 7: Validate the ranking.

Fig. 9 Steps of IRP method for ranking layouts

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, Cool and Kress to yield a compromise 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

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

Subject to

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

$$Y_i \ne Y_k\ \ \forall\ i,k\ such\ that\ i \ne k \tag{20}$$

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

The objective function of the model as shown in equation (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 equation (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 Figure 10) and multiple time periods, T=5. The data set has been taken from (Moslemipour and Lee, 2011.)

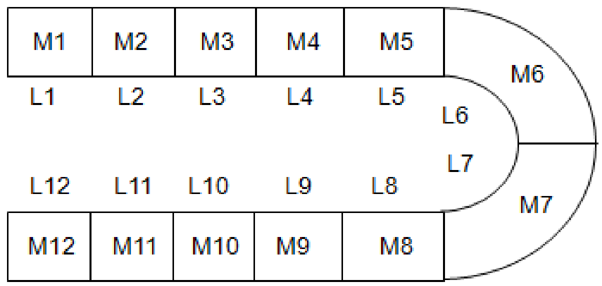

Fig. 10 U-shaped facility layout for N=12

The adjacency matrix, separation matrix and waste flow time matrix are empirically generated (refer Appendix I). 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 Figure 11 presents the entire methodology to solve SSDFLP for the numerical illustration considered. Figure 11 also shows various tables i.e. from Table 1 to Table 12 generated while applying the proposed methodology to solve SSDFLP. Table 1 shows the pool of thirty layouts generated applying step 1.

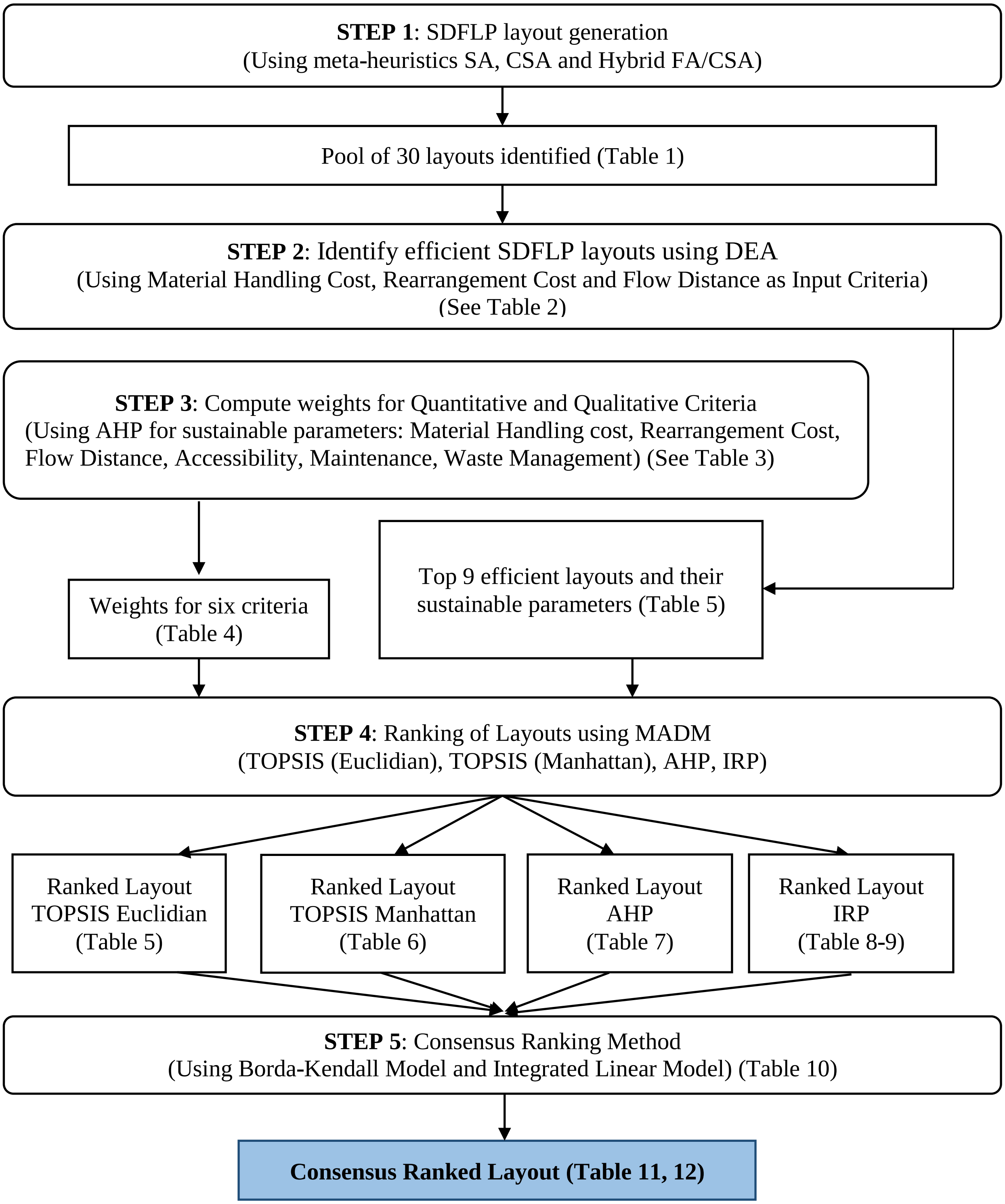

Fig. 11 Flow chart to solve SSDFLP of the numerical illustration

Table 1 Pool of Layouts

#	Material Handling Cost	Rearrangement Cost	Flow Distance
Layout 1	1182794.94	44000.00	1960.00
Layout 2	1214292.75	35000.00	2010.00
Layout 3	1217821.67	40000.00	2030.00
Layout 4	1199635.24	46000.00	1960.00
Layout 5	1220216.58	36000.00	2020.00
Layout 6	1243861.74	35000.00	2060.00
Layout 7	1242892.22	27000.00	2100.00
Layout 8	1253106.47	29000.00	2130.00
Layout 9	1242367.90	34000.00	2060.00
Layout 10	1211549.71	47000.00	2010.00
Layout 11	1220786.80	47000.00	2000.00
Layout 12	1247686.14	48000.00	2030.00
Layout 13	1232851.06	37000.00	2110.00
Layout 14	1225323.50	31000.00	2040.00
Layout 15	1210757.05	41000.00	2010.00
Layout 16	1223570.79	44000.00	2010.00
Layout 17	1231464.89	43000.00	2060.00
Layout 18	1251542.71	47000.00	2080.00
Layout 19	1240779.87	46000.00	2060.00
Layout 20	1224288.63	22000.00	2040.00
Layout 21	1241328.45	35000.00	2030.00
Layout 22	1240195.26	46000.00	2020.00
Layout 23	1211549.71	47000.00	2010.00
Layout 24	1238907.82	39000.00	2030.00
Layout 25	1235607.40	45000.00	2040.00
Layout 26	1249402.96	45000.00	2100.00
Layout 27	1245371.07	43000.00	2030.00
Layout 28	1227909.04	43000.00	2020.00
Layout 29	1202739.83	29000.00	1970.00
Layout 30	1237646.50	44000.00	2040.00

DEA using CCR (Charnes, Cooper, Rhodes) 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.

Table 2 Efficiency of layouts using DEA

#	Material Handling Cost	Rearrangement Cost	Flow Distance	Efficiency
Layout 1	1182794.94	44000.00	1960.00	1
Layout 2	1214292.75	35000.00	2010.00	1
Layout 3	1217821.67	40000.00	2030.00	0.983731471
Layout 4	1199635.24	46000.00	1960.00	1
Layout 5	1220216.58	36000.00	2020.00	0.992997233
Layout 6	1243861.74	35000.00	2060.00	0.978471475
Layout 7	1242892.22	27000.00	2100.00	1
Layout 8	1253106.47	29000.00	2130.00	0.986237675
Layout 9	1242367.90	34000.00	2060.00	0.981641469
Layout 10	1211549.71	47000.00	2010.00	0.976266125
Layout 11	1220786.80	47000.00	2000.00	0.98
Layout 12	1247686.14	48000.00	2030.00	0.965517241
Layout 13	1232851.06	37000.00	2110.00	0.979942205
Layout 14	1225323.50	31000.00	2040.00	1
Layout 15	1210757.05	41000.00	2010.00	0.986506044
Layout 16	1223570.79	44000.00	2010.00	0.982975272
Layout 17	1231464.89	43000.00	2060.00	0.976674073
Layout 18	1251542.71	47000.00	2080.00	0.961005821
Layout 19	1240779.87	46000.00	2060.00	0.96934183
Layout 20	1224288.63	22000.00	2040.00	1
Layout 21	1241328.45	35000.00	2030.00	0.97044335
Layout 22	1240195.26	46000.00	2020.00	0.975247525
Layout 23	1211549.71	47000.00	2010.00	0.992728421
Layout 24	1238907.82	39000.00	2030.00	0.970806553
Layout 25	1235607.40	45000.00	2040.00	0.973399666
Layout 26	1249402.96	45000.00	2100.00	0.962651657
Layout 27	1245371.07	43000.00	2030.00	0.97044335
Layout 28	1227909.04	43000.00	2020.00	0.979502382
Layout 29	1202739.83	29000.00	1970.00	1
Layout 30	1237646.50	44000.00	2040.00	0.971795929

Weights (sum of weights equal to 1) for each attribute were computed using AHP (preferences of expert) as given in Table 3 and Table 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 3 Ps of sustainability are important for designing a sustainable SDFLP.

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	0.1111111
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

Finally, 9 efficient layouts were identified, which are considered as alternatives ($A_1, A_2, \ldots A_9$) 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 5-9. 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 optimum (and most suitable) layout. Borda-Kendall (BAK) method and ILP were applied to obtain the consensus ranking as shown in Table 10.

Table 5 Ranking using TOPSIS (Euclidian)

#	Material Handling Cost	Rearrangement Cost	Flow Distance	Accessibility	Maintenance	Waste Management	C_i	Rank
Layout 1	1182794.94	44000.00	1960.00	353.00	296.00	70.50	0.2630691457	9
Layout 2	1214292.75	35000.00	2010.00	371.00	290.00	73.40	0.2714958234	8
Layout 4	1199635.24	46000.00	1960.00	349.00	329.00	72.10	0.3918011919	5
Layout 5	1220216.58	36000.00	2020.00	349.00	300.00	69.60	0.3239701548	6
Layout 7	1242892.22	27000.00	2100.00	385.00	300.00	66.80	0.4934014126	4
Layout 14	1225323.50	31000.00	2040.00	357.00	319.00	63.50	0.6202121921	3
Layout 20	1224288.63	22000.00	2040.00	364.00	334.00	70.70	0.6961263857	1
Layout 23	1211549.71	47000.00	2010.00	384.00	306.00	67.30	0.2903355416	7
Layout 29	1202739.83	29000.00	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	1182794.94	44000.00	1960.00	353.00	296.00	70.50	0.2997688506	8
Layout 2	1214292.75	35000.00	2010.00	371.00	290.00	73.40	0.2498246591	9
Layout 4	1199635.24	46000.00	1960.00	349.00	329.00	72.10	0.4158912977	5
Layout 5	1220216.58	36000.00	2020.00	349.00	300.00	69.60	0.3379377803	7
Layout 7	1242892.22	27000.00	2100.00	385.00	300.00	66.80	0.4882771585	4
Layout 14	1225323.50	31000.00	2040.00	357.00	319.00	63.50	0.6458886218	3
Layout 20	1224288.63	22000.00	2040.00	364.00	334.00	70.70	0.7140908988	1
Layout 23	1211549.71	47000.00	2010.00	384.00	306.00	67.30	0.3649687108	6
Layout 29	1202739.83	29000.00	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	1182794.94	44000.00	1960.00	353.00	296.00	70.50	0.125442558	3
Layout 2	1214292.75	35000.00	2010.00	371.00	290.00	73.40	0.063479172	8
Layout 4	1199635.24	46000.00	1960.00	349.00	329.00	72.10	0.159416418	2
Layout 5	1220216.58	36000.00	2020.00	349.00	300.00	69.60	0.052902153	9
Layout 7	1242892.22	27000.00	2100.00	385.00	300.00	66.80	0.090040373	7
Layout 14	1225323.50	31000.00	2040.00	357.00	319.00	63.50	0.112722093	5
Layout 20	1224288.63	22000.00	2040.00	364.00	334.00	70.70	0.120432132	4
Layout 23	1211549.71	47000.00	2010.00	384.00	306.00	67.30	0.112124318	6
Layout 29	1202739.83	29000.00	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

					Consensus Ranking	
Layout Identifier	**TOPSIS (Euclidian) Ranking**	**TOPSIS (Manhattan) Ranking**	**AHP Ranking**	**IRP 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	1202739.83	29000.00	1970.00	377.00	318.00	68.10
Layout 20	1224288.63	22000.00	2040.00	364.00	334.00	70.70
Layout 14	1225323.50	31000.00	2040.00	357.00	319.00	63.50
Layout 4	1199635.24	46000.00	1960.00	349.00	329.00	72.10
Layout 7	1242892.22	27000.00	2100.00	385.00	300.00	66.80
Layout 23	1211549.71	47000.00	2010.00	384.00	306.00	67.30
Layout 1	1182794.94	44000.00	1960.00	353.00	296.00	70.50
Layout 5	1220216.58	36000.00	2020.00	349.00	300.00	69.60
Layout 2	1214292.75	35000.00	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	1224288.63	22000.00	2040.00	364.00	334.00	70.70
Layout 29	1202739.83	29000.00	1970.00	377.00	318.00	68.10
Layout 14	1225323.50	31000.00	2040.00	357.00	319.00	63.50
Layout 7	1242892.22	27000.00	2100.00	385.00	300.00	66.80
Layout 4	1199635.24	46000.00	1960.00	349.00	329.00	72.10
Layout 23	1211549.71	47000.00	2010.00	384.00	306.00	67.30
Layout 1	1182794.94	44000.00	1960.00	353.00	296.00	70.50
Layout 2	1214292.75	35000.00	2010.00	371.00	290.00	73.40
Layout 5	1220216.58	36000.00	2020.00	349.00	300.00	69.60

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 I (from Table 13 to Table 15). All the nine efficient facility layouts are shown in Appendix II (from Table 16 to Table 24).

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 et al., 2013; 2015; Yang et al., 2013; Tayal and Singh, 2014a). We are in agreement with Yang et al. (2013) who 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 Hang, 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.

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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.

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Appendix I

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 II

Table 16 to Table 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
Period												
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
Period												
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
Period												
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
Period												
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
Period												
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
Period												
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
Period												
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
Period												
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
Period												
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