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An influential factor affecting the efficiency of a manufacturing facility is its layout. In a production facility, measure for efficiency can be based on the total cost of transporting the items between different departments and throughout the facility. However, other factors may influence efficiency of the manufacturing facility too. As such are: supporting the organisation's vision through improved material handling, material flow and control; effectively assigning people, equipment, space and energy; minimising capital investment; adaptability and ease of maintenance; as well as providing for employee safety and job satisfaction. By incorporating health and safety measures in the initial design of a facility layout, the organisation may avoid money and manpower loss resulting from industrial accidents. This paper proposes a facility layout planning methodology which integrates the occupational health and safety (OHS) features in the early design of a facility layout. The model considers transportation cost in the facility as well as safety concerns. By this means, the OHS issues are reflected prior to the construction of a facility.

Keywords: facility planning model; layout design; occupational health and safety (OHS); risk estimation

1. Introduction

Efficient design of a facility layout is recognised as one of the most important issues in manufacturing companies. Lower unit cost and higher quality are among the main objectives, and flow time and lateness are among the most commonly used performance measures of efficiency in manufacturing systems (Zolfaghari and Roa 2006). Consequently, facilities layout design is an important industrial issue as it directly and indirectly results in higher efficiency of the system (Rawabdeh and Tahboub 2006).

Facility layout has been formally studied as an academic area of research since the early 1950s (Benjaafar, Heragu, and Irani 2002). Facility layout design is regarded as the key to the performance improvement of manufacturing system (Tarkesh, Atighehchian, and Nookabadi 2009). The layout problems appear in many fields of applications. It aims to obtain the most effective facility arrangement and minimise the material handling costs (De Alvarenga and Negreiros-Gomes 2000). Facility layout design considers the design of layout, the accommodation of people, the machines and activities of a system within a physical spatial environment. Research results indicate that 20–50% of the total costs in manufacturing has direct or indirect relationships with material handling (Lin et al. 2013).

Traditionally, planning a layout starts by creating a layout diagram for the departments. The design then proceeds in iterations until a compromise is reached, which more or less satisfies all the known factors and restrictions (Whitehead and Eldars 1965). Therefore, a layout is developed using relationships among various departments, based on the judgement of experts who decide the importance of relationships between each pair of departments. However, the decision of experts can be vague and usually based on many quantitative and qualitative considerations; e.g. flow of materials between departments or the ease of supervision of employees (Karray et al. 2000).

One of the difficulties in developing and using facility layout models is the natural vagueness associated with the inputs to these models (Deb and Bhattacharyya 2003). The facility layout models consider assignment of departments to locations so that the quantitative or qualitative objectives of the model are minimised or maximised (Shouman et al. 2001). The most common objective used in quantitative methods is to minimise the materials handling cost. Qualitative methods, on the other hand, consider a subjective numerical proximity weight to express the desirability of having any two departments close to each other on the layout (Karray et al. 2000).

The majority of previous research on facility planning focused upon optimising costs and closeness relations. However, qualitative factors such as the plant safety, flexibility of layout for future design changes, noise and aesthetics must be considered as well; e.g. a proper machine tool selection has been very important issue for companies for years

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(Ayağ and Özdemir 2006). Above all, the association between facility layout and occupational health and safety (OHS) is not extensively reflected in developing models. OHS ensures the safety and health of workers by setting and enforcing standards and encouraging continual improvement in the workplace safety (OSHA 2007). It is estimated that at least 250 million occupational accidents occur every year worldwide, where 335,000 of those are fatal (ILO 2012). Indeed, proper OHS considerations confirm regulatory compliance, improves productivity and wellbeing of personnel, keeps the cost down by avoiding stoppage time following accidents and investigation; thus OHS contributes positively to the overall performance of the company (Jallon, Imbeau, and de Marcellis-Warin 2011a, 2011b). In order to ensure sustainability of OHS, risk estimation methods are used.

Risk estimation is a series of steps used to examine hazardous situations. Methods of identifying hazard and estimating risks take many forms, while offering different perspectives with different strengths and weaknesses. Each method begins with potential hazards or failures, whereas each uses a system to evaluate risks and to identify necessary protective measures. In general, any improvement to safety of a situation or machine begins with risk estimation (Giraud 2009).

OHS regulations are vast; yet, do not cover all the rules and regulations that apply to facility planning and layout design. When developing a facility layout, designers should note these constraints such as the fact that some department pairs need to be in adjacent sites for safety reasons (Tompkins 2010) regardless of the volume of material flow between them. As a result, practical facility layout should meet multiple objectives rather than a single objective (e.g. material handling cost). Multiple objectives models for layout design, especially qualitative objectives such as safety, need further research. In an effort to improve the facility layout planning models, this paper investigates how facility planning models and risk estimation tools can be integrated to provide a robust model to better meet productivity and safety requirements.

In this regards, models of facilities planning along with their objective, constraints and methodologies are studied. A similar approach was used for the risk estimation tools by comparing their characteristics and parameters. The outcome of this paper proposes a model which integrates OHS in the facility layout planning models. As a result, safety would be considered as important as other factors such as cost or space constraints. The proposed model is applied to a case study which is presented in the Part II of the paper.

2. State of the art

Facility layout problems as well as the influence of including aspects of OHS in layout models are the two main features of this research. They are elaborated in following paragraphs.

2.1 *Facility layout models*

Typical plant layout procedures determine how to arrange various machines and departments to achieve minimisation of overall production time, maximisation of turnover of work-in-process, and maximisation of factory output (Djassemi 2007). Characteristics of the facility that influence design of the layout could clearly differentiate the nature of facility planning models. Several factors and design issues are addressed in the literature, in particular: the production variety and volume, the material handling system chosen, the different possible flows allowed for parts, the number of floors on which the machines can be assigned, the department shapes, and the pickup and drop-off locations (Drira, Pierreval, and Hajri-Gaboujb 2007). These factors are detailed below.

- Specification of the manufacturing system

  The layout design generally depends on the products variety and the production volumes, from which, four types of organisation are referred to:
  - Fixed product layout
  - Product layout
  - Process layout
  - Cellular layout
- Department shapes

  Two department shapes are often distinguished:
  - Regular: rectangular
  - Irregular: polygons with 270° angle
- Department dimensions

  A department can be defined by its:

  - Area, aspect ratio, upper and lower bound
  - Fixed or rigid blocks: with fix length and width
- Layout configuration

  The limitation of available horizontal space creates a need to use a vertical dimension of the department. Hence, it can be relevant to locate the departments on several floors instead of a single one.
  - Multi-floor layout
  - Single floor layout
- Flow of material

  Backtracking and bypassing are two particular movements that can occur in flow-line layouts, which impact flow of the products.
  - With bypassing
  - With backtracking
- Layout evolution

  Nowadays, manufacturing plants must be able to respond quickly to changes in demand, production volume and product mix. Therefore, the idea of dynamic layout is considered in addition to the static layouts.
  - Static layout
  - Dynamic layout

The main objective of the facility layout model is to minimise a function related to the travel of parts; e.g. the total material handling cost, the travel time and the travel distance. Other minimisation models can be associated with space cost, rearrangement cost, equipment flow, information flow, backtracking and bypassing, traffic congestion and shape irregularities. A facility layout model can also aim to maximise the adjacency function which is the assessment of the proximity between two departments. Some researchers considered more than a single objective. A multi-objective model was introduced by Dweiri and Meier (1996) aiming at simultaneously minimising the material handling flow and the equipment flow and the information flow. Chen and Sha (2005) combined objectives into a single one by using a linear combination of the different objectives.

2.2 *Facility planning approaches*

Since the late 1950s a number of algorithms have been developed to solve the facility layout model, classified as:

(1) **Optimal algorithms:** these algorithms, which were developed to solve quadratic assignment problems (QAP), fall into two classes:

   (a) Branch and bound algorithms; e.g. Burkard and Rendl (1984); Roucairol (1987); Kim and Kim (2010); Ghaderi and Jabalameli (2012); Görtz and Klose (2012); Ahmed (2013); Gendron, Khuong, and Semet (2013).

   (b) Cutting plane algorithms; e.g. Burkard (1984); Chouman, Crainic, and Major (2009); Vasilyev and Klimentova (2010); Brandenberg and Roth (2011); Gollowitzer, Gendron, and Ljubic (2013).

Common disadvantages of optimal algorithms are the high memory and computer time requirements, while the largest problem solved optimally is a problem with 15 departments. This has encouraged researchers to use sub-optimal algorithms.

(2) **Sub-optimal algorithms:** many researchers developed sub-optimal algorithms to also deal with QAP. These algorithms are classified as: (i) construction algorithms in which a solution is constructed from scratch, (ii) improvement algorithms in which an initial solution is improved, (iii) hybrid algorithms which are combinations of two optimal or sub-optimal algorithms, and (iv) graph theoretic algorithms.

Based on these approaches, computerised techniques for the design or the improvement of a layout are proposed. Some of them are CRAFT, COFAD, CORELAP, ALDEP, PLANET, SHAPE, MULTIPLE (Bozer, Meller, and Erlebacher 1994) and BLOCPLAN (Katzel 1987). The Systematic Layout Planning (SLP) method of Muther and Mogensen (1973) is not only a proven tool in providing layout design guidelines but is still widely used among enterprises and the academic world (Chien 2004).

Major drawbacks of the aforementioned approaches lie in the fact that the search for the best layout is not very efficient and the multi-objective nature of the facilities layout models is not considered (Hillier and Connors 1966). Many studies focused on new and recent developments rather than conventional approaches to overcome these drawbacks. Intelligent techniques are presented as new advancements to tackle the problem.

(3) **Meta-heuristics algorithms:** different meta-heuristics algorithms and techniques are presented to solve facility planning models; the most well known of these systems are: neural networks (e.g. Zhang and Huang 1995; Tsuchiya, Bharitkar, and Takefuji 1996; Cook, Ragsdale, and Major 2000), genetic algorithm (e.g. HOPE by Kochhar, Foster, and Heragu 1998; MULTI-HOPE by Cheng, Gen, and Tozawa 1995; Kochhar 1998; Hamamoto 1999), simulated annealing (e.g. Heragu and Alfa 1992; Meller and Bozer 1996; Misevicius 2003), tabu-search (e.g. Chiang and Kouvelis 1996; Abdinnour-Helm and Hadley 2000) and ant colony optimisation (e.g. Solimanpur, Vrat, and Shankar 2004; Pour and Nosraty 2006; Hani et al. 2007).

(4) **Expert systems:** an expert system is defined as a special purpose computer programme used to imitate the decision making process of a human expert in a specific knowledge domain of limited scope (Shouman et al. 2001). Several expert systems have been proposed for the facility layout models; as such are KBML (Sunderesh and Kusiak 1990), IFLAPS (Kumara, Kashyap, and Moodie 1988), FADES (Fisher and Nof 1984), as well as the models presented in Harraz (1997) and Sirinaovakul and Thajchayapong (1994).

(5) **Fuzzy systems:** they provide a formal system for representing and reasoning with uncertain information. Several implementations of the fuzzy system are proposed, including the research by Dweiri and Meier (1996), Raoot and Rakshit (1993), and Whyte and Wilhelm (1999).

(6) **Intelligent hybrid systems:** hybrid approaches aim to integrate more than one technique when solving a specific problem. Some of the proposed models are presented by Chung (1999), Cheng, Gen, and Tozawa (1995), Pham and Onder (1992), and FLEXEPRET by Adedeji and Arif (1996).

There are plenty of tools and approaches which allow taking into account different aspects of a facility layout model and which provide solutions for a relatively large number of problems. From the numerous models and methods proposed for the abovementioned approaches, Table 1 elaborates on some of them.

2.3 *OHS in facility layout planning*

The implementation and certification of quality, environmental and OHS systems has been a major activity for many organisations in light of increasing pressure from their internal and external stakeholders including the regulatory bodies, community, customers, employees, suppliers and the government (Zutshi and Sohal 2005). However, providing safe and pleasant environment for personnel should be considered as early as when designing the layout of a facility.

The relationship between facilities layout and OHS has not been researched extensively. Chang and Liang (2009) developed a model, based on a three-level multi-attribute value model approach, in order to evaluate the performance of process safety management systems of paint-manufacturing facilities.

Fernández-Muñiz, Montes-Peón, and Vázquez-Ordás (2007) developed a Safety Measurement System Scale, from the results of a questionnaire survey of 455 Spanish companies, in order to guide the safety activities of organisations. Following dimensions are considered: (i) a safety policy reflecting the organisation's principles and values; (ii) promotion of workers' involvement in safety activities; (iii) employee training; (iv) communication and transference of information about the risks; (v) action planning to avoid accidents; and (vi) control or feedback on actions taken in the organisation.

Terrier (2003) presented a guideline to take into account the risk of accidents and occupational diseases in the design phase of workplace implementation. This would enable avoiding unsatisfactory and technical difficulties in future workplace improvements. Tompkins (2010) presented the human factor risks as one of the criteria to be considered in the prioritisation matrix for facilities design. In developing facilities design alternatives, designers need to consider the human factor risks. In that matrix, this criterion is compared using weights with other criteria such as the total distance travelled, manufacturing floor visibility, overall aesthetics, space requirements, people requirements etc.

The use of risk analysis when designing a facility is mentioned by Brauer (2006). The author argues that the best time to incorporate safety into a facility is during the planning and design of a new facility or the modernisation of an existing facility. A tool consisting of a list of safety considerations in facility planning is also presented, in which, a facility design is broken into several components, namely: (i) site and siting; (ii) building or facility; (iii) interior and occupancy; (iv) workstations; (v) equipment; and (vi) operations, processes or activities.

Moatari-Kazerouni, Agard, and Chinniah (2012) developed a comprehensive list of safety criteria or facility managers to consider in the early stages of the plant design to improve OHS. These criteria reflects on: (i) safety policies reflecting the hazards caused by machinery; (ii) safety in designing material handling system and machinery movement; (iii) employees training, experience and flexibility of jobs; (iv) safety in maintenance and services; (v) characteristics of material used in the manufacturing process; and (vi) environmental aspects of safety.

Furthermore, the models for solving layout problems do not directly include OHS aspects. A new trend in designing plant layouts consists of extending the layout formulations with safety issues. Various mixed integer linear programming

Table 1. Survey of analytical solution methods for facilities layout models.

Model	Technique	Objective	Comments
PLANET (Apple and Deisenroth 1972)	Construction	Flow cost	Starts at centre, 2 facilities located at once
MAT Edwards, Gillett, and Hale (1970)	Construction	Flow cost	Allows user to assign departments to any desired location
ALDEP (Hales 1984)	Construction	Closeness	Randomly selects a department, starts at upper left corner
SHAPE (Hassan, Gary, and Donal 1986)	Construction	Flow cost	Based on generalised assignment problem
FLAT (Heragu and Kusiak 1986)	Construction	Flow cost	Departments of unequal areas, low compute time, good quality results
CORELAP (Lee and Moore 1967)	Construction	Closeness	Selects first facility depending on total closeness value
HC66 (Nugent, Vollmann, and Ruml 1968)	Construction	Flow cost	Uses criteria of Vogels' approximation in TP
LSP (Zoller and Adendorff 1972)	Construction	Closeness	High computational efforts, similar to ALDEP, flexibility
CRAFT (Buffa, Armour, and Vollmann 1964)	Improvement	Flow cost	Up to 40 departments, does not perform well for departments of unequal areas, uses 2- and 3-way exchanges for smoothing irregular shapes
H63 (Nugent, Vollmann, and Ruml 1968)	Improvement	Flow cost	Only pairwise exchanges between adjacent departments, only for departments of equal areas, based on a move desirability table
HC 63–66 (Nugent, Vollmann, and Ruml 1968)	Improvement	Flow cost	Limits the exchanges only to departments which lie on a horizontal, vertical or diagonal line, only for departments of equal areas, a modification of H63, allows exchange of non-adjacent departments.
Revised Hillier (Picone and Wilhelm 1984)	Improvement	Flow cost	Uses H63, considering four-way perturbations, produces solutions at least as good as H63, more computation time than H63
COFAD (Tompkins and Reed 1973; James and Ruddell 1976)	Improvement	Flow cost	MHS selection, uses CRAFT, jointly considers layout and material handling system, more realistic layouts
DISCON (Drezner 1980)	Hybrid	Closeness	Dispersion phase provides good starting points, difficult to justify the outcome, uses a two-phase algorithm of dispersion-concentration
KTM (Kaku, Thompson, and Morton 1991)	Hybrid	Flow cost	Uses two- and three-way exchanges, a combination of construction and improvement, very good results within very little computer time
FLAC (Scriabin and Vergin 1985)	Hybrid	Flow cost Closeness	Has three stages, a combination of construction and improvement
Wheel Expansion (Eades, Foulds, and Giffin 1982)	Graph Theoretic	Adjacency	Similar to Deltahedron
Branch and Bound (Foulds and Robinson 1978)	Graph Theoretic	Adjacency	Obtain optimal solution, a require maximal planar graph
Deltahedron (Foulds and Robinson 1978)	Graph Theoretic	Adjacency	Avoid the testing of planarity
FADES (Fisher and Nof 1984)	Expert System	Flow cost Closeness, Materials handling cost	Knowledge-based approach, for solving general facility design problems, selecting equipment that meets the required technology level and performing economic analysis, written in prologue
IFLAPS (Kumara, Kashyap, and Moodie 1988)	Expert System	Adjacency	In FORTRAN, does not involve paired comparisons between departments or the overall, relationship between various departments
KBML (Sunderesh and Kusiak 1990)	Expert System		For machine layout in automated manufacturing systems, a forward-chaining inference strategy is utilised
(Tsuchiya, Bharitkar, and Takefuji 1996)	Neural Network		Near-optimum parallel algorithm, for an N-facility layout problem, BEING capable of generating better solutions over the existing algorithms for some of the most widely used benchmark problems
HOPE (Kochhar, Foster, and Heragu 1998)	Genetic Algorithm		For solving single floor facility layout problem, considered departments of both equal and unequal sizes, results indicated that GA might provide a better alternative in a realistic environment where the objective is to find a number of reasonably good layouts

(*Continued*)

Table 1. (*Continued*).

Model	Technique	Objective	Comments
MULTI-HOPE (Kochhar 1998)	Genetic Algorithm		Multiple-floor layout problems, extends HOPE algorithm, averagely gives a better solution than existing multi-floor layout algorithm
Dweiri and Meier (1996)	Fuzzy System	Flow cost Closeness	AHP is used to find the weights of qualitative and quantitative factors affecting the closeness rating between departments, a modified version of CORELAP (FZYCRLP) is used
Raoot and Rakshit (1993)	Fuzzy System	Flow cost Closeness	Considers organisational links optimisation. A linguistic pattern approach for multiple criteria facility layout problems.
FLEXEPRET (Adedeji and Arif 1996)	Intelligent Hybrid System		A fuzzy-integrated expert system, generates the best layout that satisfies the qualitative as well as the quantitative constraints on the layout problem, VP-Expert is used
Chung (1999)	Intelligent Hybrid System		A neural expert system, creates effective multi-bi-directional generalisation behaviour, goal-driven layout design experience

models were proposed to reduce financial costs, in which certain aspects of safety were also considered (Penteado and Ciric 1996; Papageorgiou and Rotstein 1998; Patsiatzis and Papageorgiou 2002; Patsiatzis, Knight, and Papageorgiou 2004). Some artificial intelligent techniques were proposed which consider both quantitative and qualitative factors, including safety and ergonomics. As such, Pham and Onder (1992) developed a knowledge-based system for optimum workplace design. The combination of knowledge-based technology, genetic optimisation methods and database technology is proved to be an effective way to build powerful knowledge-based systems for solving complex ergonomic design problems. In the research by Carnahan and Redfern (1998), a genetic algorithm is applied to the problem of designing safe lifting tasks within the constraints of the work place. Also, Pham and Onder (1991) proposed an expert system for ergonomic workplace design by using a genetic algorithm approach.

In order to evaluate OHS in a facility, potential hazards of the layout design should be identified and risk estimation be conducted. Risk estimation is the process during which managers should analyse the potential impacts of the identified risks to the organisation (Lee, Lv, and Hong 2013). It is traditionally based on collecting and evaluating data on severity of an injury and probability of occurrence of the event. In other words, risk is reduced when a protective action such as change of design, use of safeguard or application of safe procedure is implemented, that meaningfully reduces severity of injury or probability of occurrence of harm (Etherton 2007). The severity of harm can be estimated by taking into account:

- the severity of injuries or damage to health; e.g. slight, serious or fatal
- the extent of harm; e.g. to one person or to several people

Probability of occurrence of harm can be estimated by taking into account:

- Nature of the exposure of people to the hazard
  - reason to access the hazard zone, e.g. for normal operation, correction of a malfunction, maintenance or repair
  - nature of access; e.g. manual feeding of materials
  - time spent in the hazard zone
  - number of people requiring access
  - frequency of access
- Occurrence of a hazardous event
  - reliability of statistical data
  - accident history
  - history of harm to health
  - risk comparison
- Technical and human possibility of avoiding or limiting the harm
  - the people involved i.e. who may have been exposed to the hazard (skilled or unskilled workers)
  - how quickly the hazardous situation could lead to harm, e.g. suddenly, quickly or slowly
  - awareness of risk, e.g. generally available information, user manuals, direct observation, warning signs and warning devices on the machinery
  - the human capacity to avoid or limit harm, e.g. reflexes, agility, and possibility of escape
  - practical experience and knowledge, e.g. knowledge of the machinery or of similar machinery or the absence of experience or knowledge.

3. Research objectives and methodology

Minimising material handling and transportation cost is one of the most researched objectives in facility layout models, but it is not the only factor that must be taken into account when designing a layout. Other factors such as travel time and distance between departments, equipment and information flow, space and rearrangements costs, backtracking and bypassing or traffic congestion are also significant. So is the OHS in regard to the facility arrangements and equipment, building and the personnel.

The objective of this paper is to propose a facility planning model which integrates the OHS aspects in layout design of a facility. The model is based on the cost-reduction objective while it does not disregard safety of locating departments close to each other. In other words, the model would value OHS as an important factor as cost in locating departments in the layout.

Pursuing this objective, the overall research methodology consists of the following stages:

(1) Facility layout planning models as well as risk estimation tools were reviewed.
(2) A risk estimation tool is proposed for being included in the facility planning model.
(3) A facility planning model is developed which embraces the concept of integrated OHS in layout design.
(4) Restrictive assumptions, for which the proposed facility planning model is valid, are presented.

4. A model for integrating OHS in facility planning

The model consists of four steps. The first step concentrates on traditional cost factors. The second step evaluates the layout by considering the OHS aspects. The third step proposes designing a first layout based on the cost factors (if an existing layout does not already exist). Finally, the fourth step explains how the former layout can be adjusted based on the safety aspects, and how the layout is improved by exchanging the positions of departments. As a result, the layout design is improved by inclusion of OHS aspects.

Inputs to the model are: an initial/existing layout or a ‘from-to’ chart as input data for the flow cost, and any constraint for considering a facility having a fixed-position with all restrictions such as two departments must not be located close to each other at any cost. Following sections explains the steps of the model in details.

4.1 *Step I: material handling and transportation cost factor*

The first step concentrates on the relative placement of departments as measured by total material handling and transportation cost for the layout. Material handling and transportation cost between departments is calculated by multiplying ‘number of loads’ by ‘rectangular distance between departments centroids’ by ‘cost per unit distance’ (Tompkins 2010). Therefore, the initial inputs are the load matrix (‘from-to’ chart), the distance matrix, as well as the cost of carrying any material per unit distance.

In this regards, the first step is to determine centroids of departments and calculate rectilinear distance between the centroids. Obtained values result in creating the distance matrix.

Next step is to develop the material handling and transportation cost matrix. Material handling and transportation costs between pairs of departments are calculated by using Equation (1). These values configure the cost matrix.

$$Z = \sum_{i=1}^{m} \sum_{j=1}^{m} f_{ij} d_{ij} c_{ij} \tag{1}$$

where, i and j are the departments, m is the total number of departments, f_{ij} is the flow of material from the ‘from-to’ chart, d_{ij} is the distance from the distance matrix and c_{ij} is the cost of carrying any material.

Subsequently, one should look for the highest value in the material handling and transportation cost matrix. Five cost categories will be defined according to their relative cost portions, where category 5 contains the highest cost values and category 1 the lowest (see Table 2).

The ranks assigned to the cost categories indicate the relative importance in closeness of the departments based on the cost factor. Considering that a higher transportation cost value states being more economical to place the departments closer to each other, these ranks are defined as: A – absolutely necessary, E – especially important, I – important, O – ordinary closeness OK and U – unimportant. From a practical perspective, it is expected that more than half the pairwise combination of departments will have a relationship of U. It is reasonable to expect less than 5% of the

Table 2. Material handling and transportation cost categories.

Cost categories	Cost ranks	% of Occurrence of cost ranks
Category 1 (lowest)	U	More than 50% have U
Category 2	O	Less than 40% have A, E, I or O
Category 3	I	Less than 25% have A, E or I
Category 4	E	Less than 12% have A or E
Category 5 (highest)	A	Less than 5% have A

pairwise combinations to have A relationships, less than 12% to have either A or E relationships, less than 25% to have either A, E or I relationship, and less than 40% to have A, E, I or O relationships. Even with a high degree of sparseness in the layout design, the number of pairwise combinations can become unmanageable. Hence, caution must be used when dealing with a large number of departments (Tompkins 2010).

The relative importance in closeness of the departments based on the cost factor can be demonstrated as a cost relationship diagram (Figure 1).

4.2 *Step II: OHS evaluation*

The second step concentrates on including OHS in the model. To begin with, the risk scenarios need to be developed. These scenarios are related to safety issues regarding the placement of departments versus each other in the initial layout.

For each risk scenario, qualitative levels of the five risk parameters have to be identified. These risk parameters are (1) severity of harm, (2) frequency of exposure to the hazard, (3) duration of exposure to the hazard, (4) probability of occurrence of a hazardous event and (5) technical and human possibilities of avoiding or limiting the harm.

These parameters and their corresponding risk levels are presented in following paragraphs. The number of levels for each parameter has been determined from the equivalent scales as explained by Chinniah et al. (2011). Since these risk parameters are qualitatively scaled, they need to be transformed to quantitative measures in order to facilitate adopting them in the model. Therefore, a rating system is used in which quantitative values were assigned to levels of each risk parameter as their rates (see Tables 3–7). These values are based on a 1–5 rating scales, where 1 indicates the lowest and 5 is the highest risk. The tool is developed and tested in Moatari-Kazerouni, Chinniah, and Agard (2014a) and the main points are summarized here.

- Severity of harm (*S*)

Severity of harm is defined as hazard in term of potential to cause harm. The likely effect of a hazard can be rated as in Table 3. The ranks are actual values which are used in calculating risk.

- Probability of occurrence of harm (Ph)

It is estimated by four parameters. These parameters and their risk levels are addressed in Tables 4–7.

  - Frequency of exposure to the hazard (Exf)
  - Duration of exposure to the hazard (Exd)
  - Probability of occurrence of a hazardous event (Pe)
  - Technical and human possibilities to avoid or limit the harm (*A*)

Table 3. Severity of harm.

Severity of harm (*S*)	Rank
Slight injuries (bruises) requiring no first aid or injuries requiring first aid but without lost time	1
Injuries requiring more than first aid (assistance) and with lost time or when there is irreversible harm and slight disability, but the employee is able to return to the same job	2
Serious disability, the employee being able to return to work, but perhaps not to the same job	3
Permanent disability, and the employee can no longer work	4
One or more deaths	5

Table 4. Frequency of exposure to the hazard.

Frequency of exposure to the hazard (Exf)	Rank
Less than once per year	1
Annually	2
Monthly	3
Weekly	4
Daily to continuously, i.e. several times per hour	5

Table 5. Duration of exposure to the hazard.

Duration of exposure to the hazard (Exd)	Rank
<1/20 of work time	1
1/10 of work time (45 min per 8 h shift)	2
1/5 of work time (90 min per 8 h shift)	3
Half of work time (1/2) (4 h per 8 h shift)	4
Continuously during work time	5

Table 6. Probability of occurrence of a hazardous event.

Probability of occurrence of a hazardous event (Pe)	Rank
Negligible	1
Unlikely	2
Possible	3
Likely	4
Significant	5

Table 7. Technical and human possibilities to avoiding or limiting the harm.

Technical and human possibility of avoiding or limiting the harm (A)	Rank
Highly significant	1
Significant	2
Somewhat likely, with some conditions	3
Unlikely	4
Nil	5

To calculate the risk value for each of the risk scenarios, quantitative values assigned to the five parameters are used in the following equation.

$$\text{Risk value } (R) = \text{Severity of harm } (S) \times \text{Probability of occurrence of harm (Ph)}$$

$$\begin{aligned}\text{Probability of occurrence of harm (Ph)} = {} & \text{Frequency of exposure to the hazard (Exf)} \\ & + \text{Duration of exposure to the hazard (Exd)} + 2 \\ & \times \text{Probability of occurrence of a hazardous event (Pe)} \\ & + \text{Possibility of avoidance } (A)\end{aligned}$$

The mathematical relations between the parameters, as well as the weight assigned to each of them, have been adjusted according to different risk estimation approaches introduced in literature. It includes all the risk parameters highlighted in ISO 12,100, and is used to calculate the risk value for each scenario. Risk is calculated by multiplying the qualitative value of S by the qualitative value of Ph. This function is similar to the approach used in the BT (Worsell and Ioannides 2000) and Gondar (Design 2000) risk estimation tools.

Table 8. Risk value example.

Scenario	S	Ph				Risk value $R = S \times (\text{Exf} + \text{Exd} + 2 \times \text{Pe} + A)$
		Exf	Exd	Pe	A	
S	S5 3	Exf8 5	Exd5 5	Pe2 2	A1 1	*45*

To calculate a numerical value of the probability of occurrence of harm (Ph), an approach similar to that applied in SUVA (Bolier and Meyer 2002) and NORDIC (Mortensen 1998) risk estimation techniques was used. Four parameters are added: frequency of exposure to the hazard (Exf), duration of exposure to the hazard (Exd), probability of occurrence of a hazardous event (Pe) and possibility of avoidance (A). In this function, the weight for the Pe value is considered to be twice that of the other parameters. This is because the likelihood of occurrence of a hazardous event, which may be of a technical nature (e.g. system reliability) or caused by a person (e.g. error, fatigue), has a higher rank than the other parameters (Bolier and Meyer 2002).

To explain thin risk estimation method, an example would be the noise hazard that occurs in operating large panel press. The ambient noise is above 85 dB which cause a hazardous situation and workers are in the vicinity. Table 8 demonstrates assigning the numerical values of risk parameters and calculating the risk value for this hazardous situation.

In order to evaluate the risk values, five risk categories are defined. Since the maximum number obtained from the equation is 125 and the minimum is 1, the range of risk ranks were divided to 5 equal categories from 1 to 125. Risk categories are assigned to the corresponding range as demonstrated in Table 9. Moreover, these categories are ranked by scales of 1 to 5. A higher risk value indicates being less safe to place the departments closer to each other; therefore, 1 indicates the lowest and 5 is the highest closeness importance based on the safety factor.

The relative importance in closeness of the departments based on the safety factor can be demonstrated as a safety relationship diagram (Figure 2).

4.3 *Step III: layout design considering the cost factor*

This step proposes how the departments should be located in the layout when considering the cost aspects.

For that, facility planners use the techniques explained in Section 2.2. The traditional approach can be used for locating the other departments in the layout; i.e. pair of departments with higher cost value should be placed close to each other (Tompkins 2010).

The initial departments to be placed in the layout are the 'fixed-positioned' departments which are considered as constraint inputs to the model. These departments have predefined positions in the layout and their locations cannot be swapped with other departments.

The procedure is repeated until all departments are positioned in the layout.

However, if an initial layout already exist and performs correctly considering the material handling and transportation cost, step IV may directly be applied. This is applicable when this proposed methodology is applied to an existing layout, and for redesigning and improving the layout based on the OHS issues.

4.4 *Step IV: layout improvements considering OHS aspects*

In choosing which department pairs to enter the layout, this model suggests considering cost factor, followed by the safety aspect. However, the decision can be effected by different issues such as the priorities set by the company or the

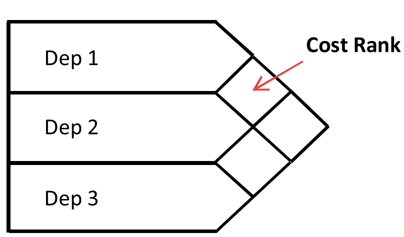

Figure 1. Material handling and transportation cost relationship diagram.

Table 9. Risk value evaluation.

Risk value ranges	Risk categories	Safety ranks
1–25	Very low	5
26–50	Low	4
51–75	Medium	3
76–100	High	2
101–125	Very high	1

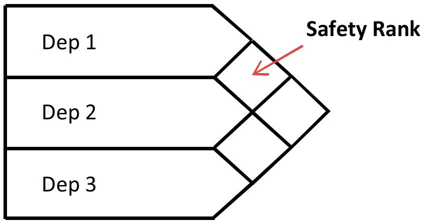

Figure 2. OHS relationship diagram.

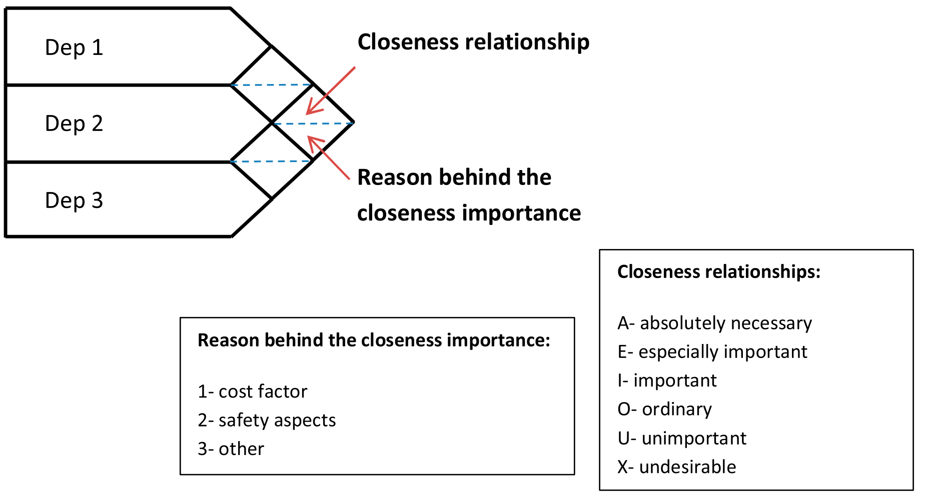

Figure 3. Safety–cost relationship diagram.

facility planner's opinion. Therefore, it is recommended that, to the extent possible, to take into account both safety aspects and cost factors. In order to better guide facility planners in their decision making, a safety–cost relationship diagram can be designed as illustrated in Figure 3. The safety–cost relationship diagram is very similar to the Relationship Chart (Tompkins 2010). In this diagram, the reason behind the importance of locating two departments close to each other is indicated, based on criteria of cost, safety as well as the opinion of the facility planner. This diagram would guide the facility planner in making decisions, when both safety and cost have significant influence. Thus, deciding the location of departments in the first layout design (step III) is influenced if safety issues recommend on the proximity of the departments.

Therefore, the new layout design process would start with facility planning group to prepare the safety–cost relationship diagram by comparing the 'material handling and transportation cost relationship diagram (Figure 1)' and 'OHS relationship diagram (Figure 2)'. They compare the cost and OHS issues from these two latter diagrams and identify what is the importance rank of positioning two departments close to each other. Their reasons can be because of (1) being more cost efficient to locate the two departments closer, (2) it is safer to have the two departments further or closer to each other and (3) other factors such as flow of information among the two departments affect their proximity. Accordingly, the safety–cost relationship diagram is prepared and based on that, the improved layout design will be portrayed.

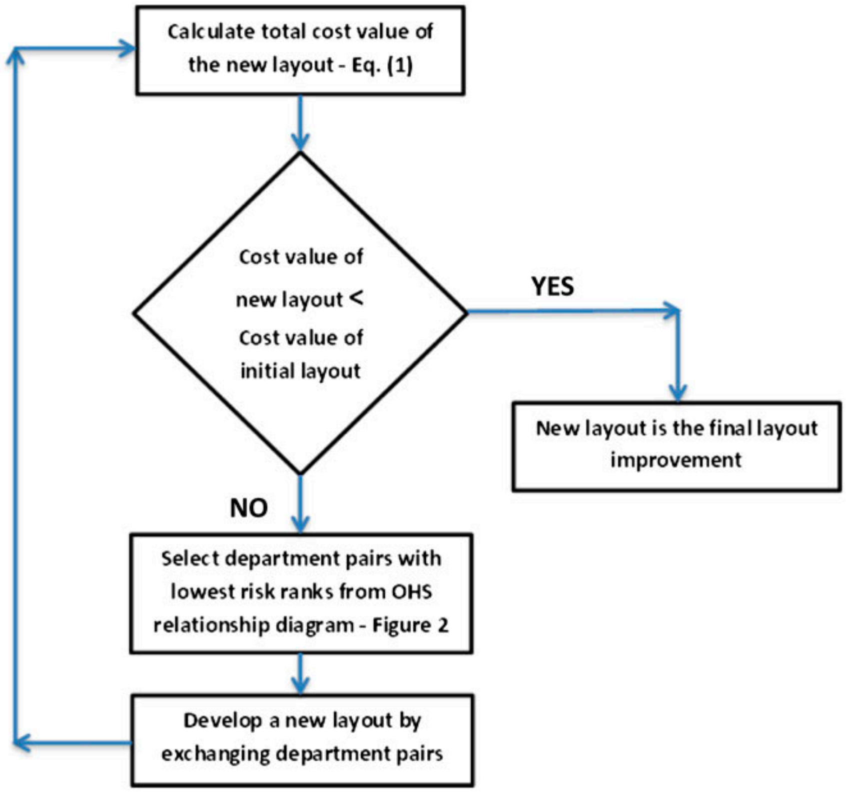

Figure 4. Layout improvements considering OHS aspects.

To obtain an improved layout design, exchanges of departments should be considered. It is to make improvements by exchanging pairs of departments iteratively until no further improvement is possible.

In this regards, the material handling and transportation cost matrix should be designed for the new layout and the total cost value be calculated by using Equation (1). The total cost value of the new layout is compared with the initial layout. If the cost value is lower for the new layout, it is determined that the new layout is our final layout improvement.

In the situation when the total cost value of the new layout is higher than the initial layout, exchanging pairs of departments must be considered. In this regards, the OHS relationship diagram (Figure 2) should be used. In this diagram, the department pairs with the lowest risk rank are considered as candidates for being exchanged. The risk value among these departments is low; hence it is not critical to reposition them for creating a new layout.

After exchanging locations of these departments, changes in the total cost value are determined. If exchanging of departments yields to a lower cost value, the exchange is made, which constitutes iteration. Exchanging is repeated until no further cost reduction is possible, while the safety concerns of positioning the departments close together must not be undermined either. Figure 4 summarises this procedure.

5. Benefits and restrictions of the integrated model

The proposed model uses an existing layout or a 'from-to' chart as input data for the flow cost. It measures the 'risk values' to evaluate the OHS aspects. These two factors can be used in agreement with each other when developing a layout. Including safety in the facility planning model leads to considering OHS in the facility as early as designing its layout, therefore reducing the chances of encountering with unsafe conditions triggered from layout design.

However, the improvements offered by the proposed model are not limited to designing a new facility layout. The model can also be applied to the current layout of an existing facility in order to ensure improvements with respect to OHS aspects. For this matter, the traditional approach of layout design is used for designing the facility layout with the material handling and transportation cost being the main factor in locating the departments. In order to adapt the layout with the OHS aspects, it can be modified by application of the 'Layout Improvements' steps of the proposed model.

Furthermore, the OHS aspects are considered quantitatively in this model, the safety relationships for locating departments are quantified. Proposed model can handle small to medium-sized problems because filling out each entry in the 'from-to' chart or assessing the risk scenarios would not be practical. It is an improvement-type methodology that may starts with an initial layout. Nevertheless, improvements in the layout are sought through department exchanges. The model follows a heuristic and does not guarantee an optimal solution. While searching for a better solution, the model picks only the best estimated exchange in each iteration. It also does not look back or forward during the above search. Such a solution is likely to be only locally optimal. Furthermore, the model is path-oriented and the final layout is dependent on the initial layout. Therefore, it is biased by its starting condition which is the initial layout.

The model is flexible in respect to the department shapes and as long as the department is not split, it is not restricted to rectangular departments. By using dummy extensions, the model can be applied to non-rectangular shapes. This may lead to irregular shapes both for the individual departments and the plant layout itself.

There are also a few assumptions that should be considered for applying the model. The moving costs are not dependent on the equipment utilisation. Besides, moving costs are linearly related to the length of the move. Moreover, if more than one hazardous situation (risk scenario) exists among two departments, the risk value for each scenario is calculated, and then the maximum values of those scenarios is considered as the risk value between the two departments. In such a case, the importance weight assigned to the risk value of scenarios is the same and equal to one.

6. Conclusion

Facility layout is one of the key areas which have significant contributions, in terms of cost and time, towards productivity in a manufacturing system. In developing facilities layout design, it is important to consider aspects such as the layout characteristics, material handling requirements, unit load implied, storage strategies and the overall building impacts. Taking into account the human factor risks and OHS requirements are important issues, too. Specifically, it is imperative during the initial design phase of a new facility or in redesign and modification of an existing facility in order to give adequate considerations to OHS norms and to eliminate or minimise possible hazardous conditions within the work environment. Yet, incorporating safety during design makes economic sense because it is much cheaper to make changes during design than to negotiate change orders with a contractor or modify a facility after completion.

This research work explored how OHS should be included in the existing facility layout planning models. Therefore, the OHS aspects are considered as one of the essential factors to be considered in the design or modification of a facility layout. In this paper, facility layout planning models as well as those which integrate OHS were reviewed. In a previous study risk estimation tools were reviewed and a risk estimation tool was proposed, in which, the risk value is quantitatively measurable; hence easier to be merged into a facility planning model. Finally, a model is developed which embraces the concept of integrated OHS in facility layout design. This model chooses the best layout design according to both OHS aspects and material handling and transportation cost. Accordingly, facility designers can make decisions when the OHS aspects should take over the cost factor or vice versa.

Further research can evaluate the practicality of the proposed model in an existing facility or one in a layout design phase. In order to do so, Part II of the paper concentrates on application of the model to a layout design changes of the kitchen at a hospital, as real-world case study.

A detailed application of the present methodology may be found in Moatari-Kazerouni, Chinniah, and Agard (2014b).

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