2004

Transport effort: a metric for the evaluation and benchmarking of automotive assembly plants

David Paul Sly
Iowa State University

Recommended Citation

Sly, David Paul, "Transport effort: a metric for the evaluation and benchmarking of automotive assembly plants " (2004). *Retrospective Theses and Dissertations*. 817.
https://lib.dr.iastate.edu/rtd/817

Transport effort: A metric for the evaluation and benchmarking of automotive assembly plants

by

David Paul Sly

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Industrial Engineering

Program of Study Committee:
John Jackman, Major Professor
Patrick Patterson
Sigurdur Olafsson
Richard Poist
Russell Laczniak

Iowa State University

Ames, Iowa

2004

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

Graduate College
Iowa State University

This is to certify that the doctoral dissertation of

David Paul Sly

has met the dissertation requirements of Iowa State University

Signature was redacted for privacy.

Major Professor

Signature was redacted for privacy.

For the Major Program

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF NOTATION AND TERMS

Terms

A = Area of plant in a consistent unit (assumed as feet in this dissertation)

ADS_n = Aisle distance from the dock to S_n to L_n

AD_n = Aisle distance for AN_n (distance to closest end)

AE = Allocation efficiency, intensity component of TE

AN_n = Assembly line location along aisle for L_n

d_n = Aisle distance from the dock to the line L_n

Δ^s = Set of all possible aisle based distances from the dock to L_n sorted short =1 to long = n

DL = Horizontal distance between assembly line locations AN_n

DW = Vertical distance between aisle centers LN_n

ED_n = Euclidean distance from the dock to L_n

$I_{p,n}$ = Intensity of flow from dock to L_n in unit loads per time period for part p

IA = Intensity allocation factor

ISF = Intensity storage factor

LE = Layout efficiency factor

LI_n = Total intensity for all parts delivered from the dock to L_n

L_n = Line location n

Λ^s = Set of all possible location intensities (sorted high=1 to low=n)

LSF_n = Layout storage factor for L_n

LL = Total number of locations per assembly line

LN_n = Assembly line number for L_n

LQ = Total number of assembly lines in plant

M = Total number of parts

N = Number of total assembly locations in the plant

P = Number of parts delivered in to the plant

p = a specific part in M parts.

PD = Approximate average plant distance

$\overline{PE}$ = Average travel path efficiency for the plant

PL = Plant Length

PW = Plant Width

RD_n = Rectilinear distance from the dock to L_n

S_n = Storage location assigned to L_n

Ω_n = Off-line storage decision variable for L_n (1 if storage, 0 if not)

SL_n = The intensity of trips from storage to L_n in unit loads per time period.

$SLDS_n$ = Ratio of storage to line intensity over dock to storage intensity

TE = Transport effort value (without off-line storage penalty)

TEF = Transport effort factor (without off-line storage penalty)

TES = Transport effort value (with off-line storage penalty)

$TESF$ = Transport effort factor (with off-line storage penalty)

TW = Transport work
ψ^S = Set of all possible L_n from 1 to N

V = Volume of flow defined as the number of SKU unit loads occurring in the plant per unit time (often a day).

LIST OF FORMULAS

ABSTRACT

Automotive assembly plants are unique from other industrial facilities in that they combine high output volume with high part counts (over 4,000 per vehicle) and high variety in a product flow layout involving a large quantity of fixed position material handling equipment. While assembly plants share common factory layout issues such as, dock placement, storage placement, transport batch sizes and aisle design, it is the high material flow volumes of large and heavy products coupled with the less layout flexibility, due to fixed equipment, that make automotive assembly plants uniquely suited for the evaluation and benchmarking metrics proposed in this dissertation.

This dissertation proposes new metrics capable of evaluating and comparing automotive assembly plant designs based on the efficiency of each plant's aisle design, dock placement and intensity allocation. These performance metrics are generated from readily available information and are evaluated against hypothetical "best case" and "worst case" scenarios. These metrics have been developed for use by practitioners to design and benchmark automotive assembly plants with readily available application software such as MS Excel, AutoCAD and FactoryFLOW.

INTRODUCTION

Problem Statement

Background

New automotive assembly plants represent the most complicated and expensive industrial facilities constructed today. New automotive plant construction is exceeding $1 billion, and new vehicle/model retooling can easily cost over $300M every 3 to 7 years. With market pressures dictating shorter vehicle platform and model run times, these facility costs are becoming an increasing component of the vehicle product cost. With increasing global market competitiveness it is becoming more important for automotive manufacturers to account for, and benchmark their new plant designs to ensure an effective allocation of budgets for capital improvement.

Facilities design is taking on increased importance as industry strives to become more agile and responsive (Tompkins 1997). "Since 1955, approximately 8 percent of the U.S. GNP has been spent annually on new facilities. In addition, existing facilities must be continually modified. These issues represent more than $250 billion per year attributed to the design of facility systems, layout, handling systems, and facilities locations."

Meller and Gau, (1996) Estimate that between 20% to 50% of total operating expenses are material handling costs. A good facility design can achieve a 10% to 30% cost savings.

In order to better evaluate and benchmark different automotive assembly facilities worldwide, performance metrics are needed that accurately describe the effectiveness and efficiency of each plant's layout and material flow. These performance metrics need to be based on design information for each facility, and be generated by standard methods whose output sensitivities are known. A standard set of analysis techniques can then be employed involving tools such as AutoCAD, FactoryFLOW and MS Excel Spreadsheets that can process these key input variables into results that can be used as comparative benchmarks between dissimilar facilities.

This problem is especially complex when one considers the complexity of the product structure. In addition, the country of manufacture may dictate costs for space, labor, utilities and material handling methods that may greatly affect the overall efficiency of a particular design and production method when compared to another facility located in a different country which may produce a different product. As a result, it will be necessary to compensate for these various factors within the metrics so as to eliminate as much bias and dependence as possible.

Background Research in Assembly Plant Design

Automotive Assembly plants are "Process Focused" layouts whereby the facility is designed around the process used to manufacture a product. Key design objectives are to reduce the travel distance of the product, and its components, and to minimize space usage. In addition, the facility designer seeks to incorporate flexibility into the design, such that new vehicle types and models can be accommodated in the future with minimal facility modification.

Much research has been performed in the general field of factory design. The majority of this research focuses on the evaluation of activity relationships and material flows between activity locations within a facility. These activity locations include docks, storage areas, staging areas, light boards, and assembly locations. Computerized optimization techniques have been developed over the past 30 years in order to minimize overall travel distance (transport work) via the location of these activity areas such that priority is given to the adjacency of activities that have the highest material flow or prioritized relationship between them. Unfortunately much of this research is of minimal value to the design of "Process Focused" assembly facilities such as automotive assembly plants.

In existing automotive assembly plants, the position of the assembly lines (and thus available line locations for material delivery) are largely fixed, and can only be moved at great expense. In these facilities, the primary objective is to reduce the length of the assembly lines, remove buffer storage areas, reduce off-line storage and deliver material as close to its Point of Use (POU) as possible. Unfortunately, assembly plants naturally consist of long and thin assembly lines that are difficult to move materials around, and therefore the design of the aisle network will have a significant impact on material flows and efficiencies.

As such, only methods that incorporate the "actual layout" are effective in evaluating the design of an assembly plant, and very few of these tools exist. FactoryFLOW is one such application, (Sly 1990), as are the assembly plant benchmarking methods developed by Sly and Heid (Sly and Heid 1997).

LITERATURE REVIEW

Concepts of Material Handling Analysis

Physical work is defined as the product of a force F over a distance d, (i.e.,$W=Fd$), where d is a linear measure and force is a measure of intensity applied across that distance. In the context of material handling, travel intensity is analogous to F. The work associated with moving material over a distance d a specific number of times I can be called transport work, TW. Muther defines transport work (Muther, Hagnas 1987) as

(2.1) $$TW = I \times d,$$

where,
I is the number of moves/unit time and
d is the distance moved.

Intensity for a given part j is given by,

(2.2) $$I_j = \frac{n_j P_j}{t},$$

where,
n_j is the number of units of part j,
P_j is the dimensions of the unit of part j and
t is the time period over which the moves occur.

The total transport work for all parts is then given as

(2.3) $$TW = \sum_{j=1}^{M} I_j d_j,$$

where,
I_j is number of moves/unit time of part j,
d_j is the distance moved for move of part j and
M is the total number of parts.

Muther also extended this concept to include a rating for consistency of flow, whereby consistency refers to the variability in the actual intensity of flow per time period.

Each intensity is assigned an "-a", "-e", "-i", "-o" or "-x". An "a" represents total consistency, whereas an "x" indicates total unpredictability.

Total distance traveled by unit load devices during a specific range of time is the result of (2.3). As such, Muther (1987) defined an independent measure of intensity which he referred to as the Mag (short for magnitude). Mag is a measure of transportability, such that one Mag equals a quantity of material that:

- Can be held conveniently in one hand
- Is reasonably solid
- Is compact in shape and has some stacking qualities
- Is slightly susceptible to some damage
- Is reasonably clean, firm and stable

With the Mag value, Muther sought to eliminate the impact of pre-selected unit load sizes such that bulk moves of material of different types could be compared prior to the selection of the material move method and appropriate unit load. Substituting the Mag value for the unit load intensities in (2.3) provides an alternative measure of transport effort.

In 1963, Armour and Buffa (1963) formulated the layout problem in such a way as to represented intensity as a frequency that could be factored to include relative material handling costs. Their formulation assumes a rectangular region, R, for the plant with fixed dimensions H and W, and a collection of n required departments. For department j, the specified area a_j with dimensions (if rectangular) of h_j and w_j, is given by $a_j=h_jw_j$. Material flow is defined in a matrix $\mathbf{F}$, where each element f_{jk}, is the flow between departments j and k. $\mathbf{F}$ generally includes a traffic volume in addition to a unit cost to transport that volume. When cost is included within the flow matrix $\mathbf{F}$, it becomes a cost matrix where $\mathbf{F}$ would represent the cost per unit distance between departments j and k, with the units of dollars per unit distance (i.e. foot). Cost per unit distance is determined as the product of the material handling method cost per unit distance and the frequency of trips along that distance. The objective is to partition R into n subregions representing each of the n departments such that transport work is minimized. The objective function is given as,

$$\text{(2.4)} \qquad \min Z = \sum_{j=1}^{n} \sum_{k=1,j\neq k}^{n} f_{jk} d_{jkp} \ ,$$

where d_{jkp} is the distance (using a distance matrix) between the centroids of departments j and k in partition p. The centroidal distance is simple to calculate for rectangular departments and it is intuitive in that the mass of material is considered to move from center to center of the departments along the shortest rectilinear or Euclidean distance. However, the centroid distance measure is not realistic for many applications, as it allows material transport through departments and does not consider aisle structure (Benson, Foote 1997). In automotive assembly plants with long continuous assembly lines, the use of Euclidean or Rectilinear distances versus aisle path distances can generate significantly different results.

Since 1963 much research and development has been done in an effort to arrange departments such that material handling costs are minimized. Much of this research involved Material Flow, Relationship Analysis techniques, or weighted factor aggregations of the two.

In the literature, a layout's efficiency is typically measured in terms of material handling costs. These costs are approximated with one or more of the following parameters.

1. Interdepartmental flows - f_{ij} the flow from department i to department j
2. Unit-cost volumes - c_{ij} the cost to move one unit load one distance unit from i to j
3. Department closeness ratings - R_{ij} the numerical value of a closeness rating between departments i and j

These parameters are used in two common surrogate material handling cost functions (Francis, McGinnis, White 1992).

The first of the two surrogate material handling cost functions is based on departmental adjacencies,

$$\text{(2.5.1)} \qquad \max \sum_{i=1}^{N} \sum_{j=1}^{N} (r_{ij}) x_{ij},$$

where,
r_{ij} is the closeness rating between i and j (such as A,E,I,O,X) and
$$x_{ij} = \begin{Bmatrix} 1, & \text{if } i \text{ and } j \text{ are adjacent} \\ 0, & \text{otherwise.} \end{Bmatrix}$$

Such an objective is based on the premise that material handling costs are reduced significantly when two departments are adjacent.

The second surrogate material handling cost function is based on interdepartmental distances, which assumes that cost varies directly with distance and is given by,

$$\text{(2.5.2)} \qquad \max \sum_{i=1}^{N} \sum_{j=1}^{N} (f_{ij} c_{ij}) d_{ij},$$

where,
r_{ij} is the closeness rating between i and j (such as A,E,I,O,X),
f_{ij} is the intensity of flow between i and j, and
d_{ij} is the distance between i and j

Some of these techniques were used to design new layouts while others were used to improve existing facility configurations or search for alternatives.

Distance Methods

Several methods for measuring proximity of departments have been used in new layout design and layout improvement. These methods have used Euclidean, Rectilinear, Aisle-based Centroid-to-Centroid, and Adjacency.

Rectilinear distance is the most common distance metric used because it is based on travel along paths parallel to a set of perpendicular orthogonal axes (Tompkins, White 1984). Euclidean distance is appropriate when distances are measured along a straight line path connecting two points (for example, conveyor travel and air travel). Euclidean distances were used in (Tam and Li 1991).

Centroid to Centroid (CTC) was the most common distance metric in early research and involves computing the Euclidean distance from the center of one department to the center of the other. This method assumes that the actual input/output (I/O) point(s) for the department is unknown. Layout designs using this method tend to have a concentric structure about the department with the most connections. (Armour, Buffa 1963)

Adjacency is a relationship method. Typical adjacency matrices are defined such that if two departments share a common edge they are deemed adjacent. A modification of the adjacency method involves the determination of adjacency by using a common distance threshold (Sly FactoryPLAN 1994) (or preferably the closest I/O location (Benson, Foote 1997)) be within some minimum distance., and (Meller and Gau 1996)

Finally, distances can also be measured using actual Aisle paths, using either I/O locations defined within the department or the department's centroid and then projecting the centroid to a perpendicular point along the face adjacent to the aisle that would represent the shortest aisle path to the desired location. The use of actual distances, or at least edge-based distances (Banerjee, Zhou, Montreuil 1997) in improvement and design algorithms is rare, as the aisle network is often dependent upon the layout which cannot be determined until the from/to travel distance matrix is determined, which of course depends on knowing the layout. (Sly 1990) proposed one of the early systems for evaluating and comparing layout alternatives using actual CAD drawings of the layout in a popular CAD application called AutoCAD.

Improvements to the Aisle-based method were introduced in 1997 with (Sly and Heid) in their development of early benchmarking metrics for the evaluation of automotive assembly plant layouts with respect to indirect material handling labor. In their research, they proposed five individual methods for comparing different facilities. The first metric measured the magnitude of diagonal material flows and is given by,

$$\sum_{i=1}^{N} \sum_{j=1}^{N} (RDL_{ij} - EDL_{ij}) / EDL_{ij}, \tag{2.5.3}$$

where,
RDL_{ij} is the Rectilinear distance from dock i to line location j and
EDL_{ij} is the Euclidean distance from dock i to line location j.

The next metric is a measure of the fundamental efficiency of the aisle design and is given by,

$$\sum_{i=1}^{N} \sum_{j=1}^{N} (ADL_{ij} - EDL_{ij}) / EDL_{ij}, \tag{2.5.4}$$

where,
ADL_{ij} is the Aisle-based distance from dock i to line location j and
EDL_{ij} is the Euclidean distance from dock i to line location j.

The next metric is a measure of additional material flow due to intermediate storage between dock and a line given a specific aisle network and is given by,

$$\sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{N} (ADSL_{ijk} - ADL_{ij}) / ADL_{ij}, \tag{2.5.5}$$

where,
$ADSL_{ijk}$ is the Aisle-based distance from dock i to line location j via an intermediate storage k and
ADL_{ij} is the Euclidean distance from dock i to line location j.

The next metric is a measure of how much backtracking is caused by the aisle network design and is given by,

$$\sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{N} (ADSL_{ijk} - RDSL_{ijk}) / RDSL_{ijk}, \tag{2.5.6}$$

where,

$ADSL_{ijk}$ is the Aisle-based distance from dock i to line location j via an intermediate storage k and

$RDSL_{ijk}$ is the Rectilinear distance from dock i to line location j via an intermediate storage k

The final metric is a measure of how much storage locations and the aisle network itself increase material flow from the dock to the line, and is given by,

$$\sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{N} (ADSL_{ijk} - RDL_{ij}) / RDL_{ij}, \tag{2.5.7}$$

where,

$ADSL_{ijk}$ is the rectilinear distance from i to j via an intermediate storage k

RDL_{ij} is the Euclidean distance from i to j

In a multi-floor facility layout problem, one needs to consider the vertical distance in addition to the horizontal distance (Johnson 1982). Multi-floor problems require the user to specify data on potential lift locations and the cost to move one unit load one vertical distance unit between departments *i* and *j* (c^{V}_{ij}), as well as to specify data on the horizontal material handling costs (c^{H}_{ij}). The objective used in multi-floor problems is to

$$\min \sum_{i=1}^{N} \sum_{j=1}^{N} (c_{ij}^{H} d_{ij}^{H} + c_{ij}^{V} d_{ij}^{V}) f_{ij}, \tag{2.5.8}$$

where,

c^{V}_{ij} is the vertical cost per unit of distance from i to j

c^{H}_{ij} is the horizontal cost per unit of distance from i to j

d^{H}_{ij} is the horizontal distance from i to j

d^{V}_{ij} is the vertical distance from i to j

f_{ij} is the frequency of trips (intensity) from i to j

where, d^{H}_{ij} (d^{V}_{ij}) denotes the horizontal (vertical) distance between department *i* and department *j*. Horizontal distances between departments on different floors are typically measured between department centroids via the lift that minimizes the total horizontal distance traveled to and from the lift.

Because there are advantages and disadvantages to these two objectives, in some cases (Rosenblatt 1979) (2.5.1) and (2.5.2) are combined in a weighted criteria:

$$\min \alpha \sum_i \sum_j (f_{ij} c_{ij}) d_{ij} - (1-\alpha) \sum_i \sum_j r_{ij} x_{ij}, \tag{2.5.9}$$

where,

$\alpha \in [0,1]$

(Meller and Gau 1996) examine how to set alpha and whether an exact value is critical.

Optimization and Design Methods

Currently, most of the research involving the computation of material flow distance in the facility is oriented to layout optimization methods using the Quadratic Assignment Problem approach (QAP), the Graph-Theoretic approach and even new approaches including Mixed Integer Programming (MIP) and the design method of Axiomatic design (Meller and Gau 1996). A brief overview of these methods is presented as they relate to the use of distance and other layout related performance metrics.

QAP Approaches

The QAP approach was introduced by Koopmans and Beckman (Koopmans, Beckman 1957) to model the problem of locating interacting plants of equal areas. The objective function (2.5.2) is a special case of the facility layout problem because it assumes that all departments have equal areas, and that all locations are fixed and known a priori, as such this is represented as an improvement method. The QAP formulation is a one to one mapping between departments and locations. The cost of placing a department at a particular location is dependent on the location of the interacting departments. This dependency leads to the quadratic objective function that inspires the problem's name.

Graph Theoretic Approaches

In Graph Theoretic approaches, it is assumed that the desirability of location of each pair of departments adjacent to each other is known. (Foulds and Robinson, 1978) The area and shape of the departments are ignored (at the beginning), and each department is then represented by a node in a graph. Department adjacency relationships are represented as arcs between department nodes. The objective function is to construct a graph that maximizes the weight on the adjacencies between department pairs. The objective function is maximized if all department pairs with positive flow have an arc between them. As such, it is necessary to limit the number of arcs incident at each department and thus heuristics must be used to construct a maximally weighted adjacency graph. Finally, the actual departments are replaced with their respective nodes and the block layout is adjusted as necessary to fit within the bounds of the facility.

This method is similar to the manual methods presented by Muther (1966) in his Systematic Layout Planning approach (SLP). As such, this method is primarily a design technique. In this method, neither distance, nor the aisle network, are factors as only the concept of adjacency is relevant.

Mixed Integer Programming Approaches

The mixed-integer programming (MIP) formulation for the facility layout problem was presented by Montreuil (1990). While the model uses a distance-based objective function, it is not based on the traditional discrete (QAP) framework. Instead, it utilizes a continuous representation of a layout. The objective function is based on the product of material flow and rectilinear distance between department centroids (i.e. transport work). The standard linear programming approach is used to linearize the absolute values in the distance function. Each department is constrained to be within the facility and the maximum and minimum lengths of the department rectangles are constrained. While this MIP approach is effective, currently only problems with six or less departments can be solved optimally.

Axiomatic Approaches

Axiomatic Design Approaches are a very new and unique way to evaluate the layout of Automotive Assembly Plants. The Axiomatic Design Approach was developed by Suh as an approach to conceptual design in which a set of generalized principles or axioms are applied or copied in different situations (Suh 1990). The Axiomatic Design Approach was first applied to the Automotive Assembly Plant design problem by Houshmand and Jamshidnezhad (Web).

Axiomatic Design defines solutions to design problems in the form of products, processes or systems that satisfy needs by mapping Functional Requirements (FR) and Design Parameters (DP). The FR's represent the goals of the design and the DPs specify how FR's must be satisfied (Almstrom 1998). Suh proposed four design domains: Customer, Functional, Physical and Process Domain. FRs are defined in the functional domain in order to satisfy the needs which are defined in the customer domain. Design parameters are the outcomes of mapping FRs in the physical domain.

Houshmand and Jamshidnezhad defined their primary Functional Requirement (FR0) as "Maximize long-term return on investment" and their primary design parameter as "Redesign the assembly line toward lean production". This FR would be more appropriate for the entire enterprise as it is not plant specific. One of their three next level functional requirements was "Minimize Production Costs" (FR1) which eventually mapped to a second-level (FR14) to "Improve facility material flow".

Another way to use AD for assembly plant design would be to define another domain that uses the process DPs as its FRs within which specific assembly plant functions would be defined and mapped.

DEVELOPMENT OF THE METRIC

Problem Definition

The primary objective of this research is to devise a metric for evaluating and benchmarking automotive assembly plants. Central to this metric is the representation of critical design and operating parameters in the plant layout. As such, the metric parameters should include factors such as those discussed in the Introduction section. In addition, the metric needs to be valid for comparing different layout/assignment alternatives within a plant, and comparing dissimilar assembly plants that may even produce drastically different vehicles, in different production volumes, in different countries and with varied levels of automation.

All variables in the metric are assumed to be static and deterministic with respect to the time period for analysis. The deterministic nature of the layout of an assembly plant is attributed to the relatively long term time frames in which layout parameters (aisle designs, dock and assembly line locations) are constant. Production output, in terms of cars per day, as well as the average number of SKU's per car, and the average unit loads (or Mags) per SKU determine the intensity of unit load trips within a facility. These intensities are likely to change more frequently than are the physical attributes of a facility. On the other hand, these changes represent different layout design parameters and are driven by engineering decisions affecting the plant's output and efficiency.

As the metric is intended to be used in the evaluation and comparison of design parameter sets for a particular instant in time, it is assumed that these parameters are constant during the time frame and thus the overall method is deemed deterministic and static within that time frame.

Assumptions and Definitions

Assumptions

The following assumptions are necessary for the subsequent discussion.

1. Material is received from a dock located on the perimeter of the facility
2. Material is either delivered directly to an assembly line location or to an off-line storage location. Any material delivered to an off-line storage location is subsequently delivered to an assembly line location.
3. Aisle distances represent the shortest path travel, via the aisle network from the origination to the destination of the material flow (i.e. there is only one possible aisle path).
4. When multiple docks exist, the Aisle distance method is used to determine which dock is closest, as opposed to using the Euclidean distance method. This rule is based upon the assumption that the closest dock is that used for transfer.
5. An off-line storage location can serve multiple line locations.
6. Unit load pickup and drop off time and effort is negligible and can be ignored.
7. Additional time for turning is negligible and can be ignored (i.e., transport effort for a path involving no turns will be considered equal to a path involving several turns).

Formulation of Transport Effort

Transport Effort

Transport effort (*TE)* is defined as a measure of plant layout performance from a material handling point of view. It includes elements of plant configuration (layout component) and process configuration (intensity allocation component). The layout component is used to measure the effectiveness of the flow of materials through the plant, from the originating dock location to a destination line location, using the actual aisle network, via the shortest path within a facility of a particular size (area). An assignment component is used to measure the effectiveness of the allocation of parts to assembly line locations, as well as the volume of flow through the facility.

Similar to transport work, transport effort evaluates a layout using the basic concepts of distance and intensity. However, *TE* combines distance and intensity out of components that independently describe the efficiency of the layout design (along with its relative size), as well as the efficiency of its intensity allocation (along with the production volume applied to that allocation). In this manner, the analyst is able to use the value of *TE* for overall comparison purposes, and the component values of *TE* for analysis purposes in identifying what makes the plants different. Therefore, *TE* is a function of volume, part mapping, locations, aisle orientation, plant shape, and plant size. Part mapping is the assignment of parts to locations.

Distance Component of Transport Effort

Path Efficiency Factor

Distance as a measure of efficient plant design is difficult to use for comparative purposes when the plant size, efficiency of the aisle network, and the transport volumes (intensity) vary widely between the facilities. This problem is reflected in Figure 3.1 where the distance of a flow path is nearly the same for a relatively similar location in a plant of a different size with a different flow path efficiency.

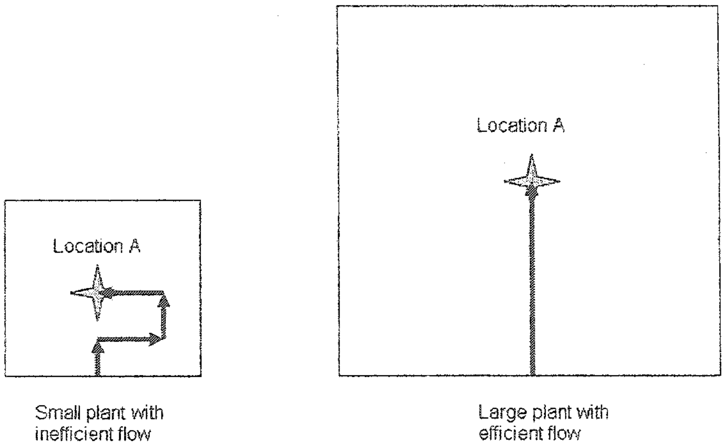


Figure 3.1. Flow Path Comparison in Different Plants

Thus the challenge is to determine the overall efficiency of a plant configuration (its aisle network) in terms of travel paths, referred to hereafter as path efficiency *PE*, independent of facility size and intensity of flow. To compute path efficiency it is important to first evaluate flow path measurement alternatives within automotive assembly plants.

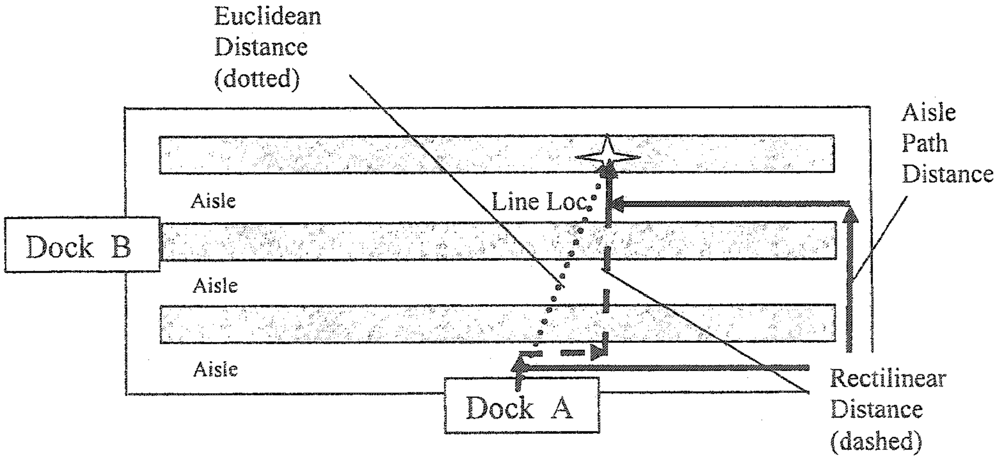


Figure 3.2. Conceptual diagram of different Flow Distance Methods

Figure 3.2. identifies three possible ways to compute travel distance within a facility namely, Euclidean, Rectilinear and Aisle based. While Euclidean and Rectilinear distances are straightforward to compute using figure 3.2, Aisle-path distances are need additional description. For the subsequent analysis, Aisle-path distances from docks were computed via

the method shown below for cross-wise flows originating at Dock A in figure 3.2. In this method, the vertical distance between assembly line centers, *DW*, is given by

(3.0.1) $$DW = PW/(LQ+1),$$

where,
PW is the width of the plant and
LQ is the quantity of locations per aisle

And the horizontal distance between line locations, *DL*, is given by,

(3.0.2) $$DL = PL/(LL+1),$$

where,
PL is the length of the plant and
LL is the quantity of assembly lines in the plant

And the travel distance along an aisle from a location to the closest vertical access aisle, AD_n, is given by,

(3.0.3) $$AD_n = \min(LL - AN_n, AN_n)DL,$$

where,
AN_n is the location on the line numbered from left to right,
starting with the number 1

Then the Aisle-path distance from the crosswise dock (figure 3.2, Dock A), d_n, is given by,

(3.0.4) $$d_n = (PL / 2.0) + (LN_n \times DW) + AD_{n,},$$

where,
LN_n is the assembly line number of the location numbered from
bottom to top starting with 1

And the Aisle-path distance from the direct dock (figure 3.2, Dock B), d_n, is given by,

(3.0.5) $$d_n = (AN_n \times DL) + (|LN_n - (LQ/2)|DW),$$

It is well known that the shortest path between two points is a straight line, thus the Euclidean distance is the lower bound for the travel distance from a dock to a line location L_n

out of the total set of line locations for the plant, ψ, as represented by the set $\psi^S = \{L_1, L_2, L_3, \ldots L_N\}$. Let the path efficiency from the closest dock to L_n, PE_n, be defined as

(3.1.1) $$PE_n = ED_n/d_n, \quad for\ n = 1, 2, 3 \ldots N$$

where,
ED_n is the Euclidean distance and
d_n is the Aisle path distance from a dock to L_n.

A value for PE_n of 1 would indicate the optimal case while a value that approaches 0 indicates a poor path.

As stated earlier, it is assumed that the closest dock is used based on aisle distance. In cases where the dock assignments are based on other factors, the metric could be modified. Aisle distances (as opposed to Euclidean) are used to provide a better estimate of actual travel. For example, Figure 3.3 shows a situation whereby the shortest Euclidean distance to the line location is obviously from Dock A, however the shortest Aisle path distance to the line location is obviously from Dock B.

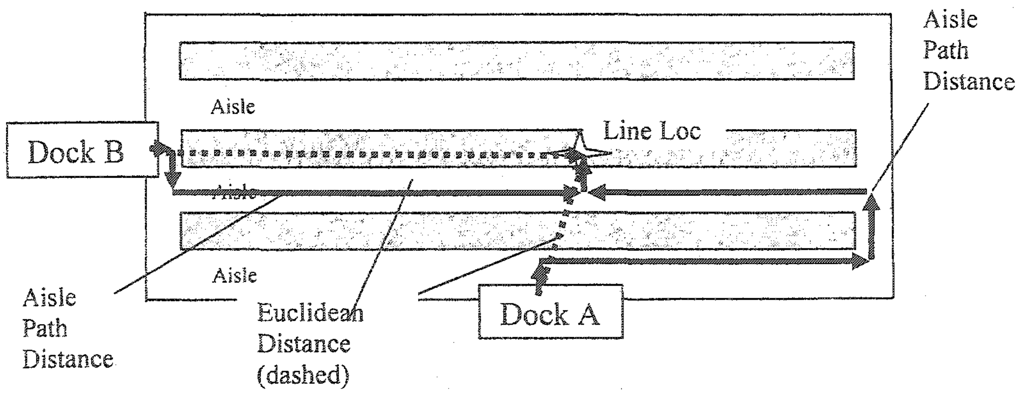


Figure 3.3. Diagram of Euclidean and Aisle Shortest Distance Discrepancy

Rectilinear distances could also provide a travel distance estimate. However, the long aisles found in automotive assembly plants makes the use of rectilinear estimates less accurate, as those aisles create backtracking flow not measured by rectilinear methods.

Figure 3.3 shows an example of backtracking flow whereby the flow path from Dock A to the line location must move a distance in the positive horizontal direction and then move again in the negative horizontal direction. The amount of distance incurred by the path in both a positive and negative direction along the same axis is referred to as backtracking flow. The long assembly lines without material travel openings along them can often create a large amount of backtracking flow when material receipt is located such that the desired material flow direction is not parallel to the aisle direction.

While a thorough evaluation of the sensitivities of using Rectilinear or Aisle distances on final results would be warranted to determine differences in results, such an analysis is beyond the scope of this dissertation. Thus the following formulations and evaluations are based entirely upon using Aisle path distances as it is obvious that Aisle path distances more accurately reflect the constraints of the aisle network.

Assembly plants have many receiving and delivery locations. Descriptive parameters for the plant path efficiency would include traditional parameter estimates such as the mean or variance. Given that the population of locations is finite, parameter estimation is based on all locations. This is accomplished by simply computing the average PE value for the plant, $\overline{PE}$, for all delivery locations in the facility and is given by,

$$\overline{PE} = \sum_{n=1}^{N} PE_n / N \tag{3.1.2}$$

where,
N is the number of locations in the plant and
PE_n is the path efficiency from the dock to L_n.

$\overline{PE}$ is the most fundamental, and independent measure of a plant's material flow efficiency. As $\overline{PE}$ is a mean, it is certain that PE_n values would vary between locations, and possibly do so significantly. In addition, it is also likely that these PE_n location variances may represent entirely different population distributions. Therefore, it is recommended that the variability and distribution of PE_n values be evaluated as $\overline{PE}$ values between assembly plants are compared, or used as a benchmark for the effectiveness of a plant's material flow design. Of course $\overline{PE}$ values do not tell the entire story relative to how large a plant is or how well flow intensities have been allocated within that plant.

Plant Size

Plant size independent of $\overline{PE}$ will obviously impact total transport effort. Thus, larger plants will have more work effort than will smaller plants given the same $\overline{PE}$ value due to the longer average distances required for the larger plant. Thus a scalar factor representing the average relative travel distance of the facility is required. A relative average travel distance is required as opposed to a specific average travel distance as the metric is intended for comparison purposes. Three potential methods to determine the average relative travel distance independent of intensity or intensity allocation would be.

1) Compute the average of the dock to line distances for all line locations using the aisle-based distance method (Direct and Crosswise rows in table 3.1).
2) Compute the square root of the area (which represents the length of one side of the facility provided that the facility was square in shape and shown as the Side row in table 3.1)
3) Compute the Euclidean distance between opposing corners of the facility. This could be done assuming that the facility was square, or actually taking into account the primary length and width dimensions of the facility (Euclidean row in table 3.1).

Table 3.1 shows the results of these methods for a 1 million square unit facility. In the first two columns, the facility is square. The last two columns are rectangular facilities with a 3 to 1 ratio for the length and width. The size of the facility and the rectangular ratio values were selected arbitrarily. Under each of the plant shapes two different aisle and line location configurations were run. The 10x25 columns refers to 10 aisles with 25 line locations each, whereas a 25x10 column refers to 25 aisles with 10 line locations each. These aisle and line location quantities have also been selected arbitrarily. The estimates shown below assume that a single dock is placed in the middle of one side of the plant. Rows labeled "Direct" and "Crosswise" are based on dock placement at the end of the plant where aisle flows would be parallel to the aisle network and on the side of the plant where aisle flows would be perpendicular to the aisle network, respectively.

Table 3.1. Average distances for a 1 million square unit plant

	Square		3-1 Rectangular	
	10x25	**25x10**	**10x25**	**25x10**
Euclidean	1414.214	1414.214	1825.583	1825.583
Side = $\sqrt{area}$	1000	1000	1000	1000
Direct	727	740	997	1004
Crosswise	1221	1181	1538	1469
Average	974	960.5	1267.5	1236.5

These results, demonstrate a significant variance in the average distances using the aforementioned different distance methods when the flows are crosswise or direct and when the facility is square or rectangular. From table 3.1, it does not appear that the quantity of aisles or aisle locations impacts the results by a relatively significant amount. As the objective of this factor is to represent the relative size and shape of the facility independent of the aisle efficiency and intensity, only the Euclidean distance or the average actual distance developed from the average of the direct and crosswise average distances is recommended for use. This recommendation is made because those values are least impacted by the number of aisles and aisle locations, they change with the shape of the facility (which is desired), and they are not dependent on a specific flow direction (thereby not introducing bias of a specific flow direction).

Since the average distance and the Euclidean distance are both approximately 30% larger for the rectangular factory as for the square factory (29% for Euclidean and 31% for Average) they both appear to be valid relative measures for facility size and shape. Thus, since the Euclidean distance of the facility is much easier to determine, it has been selected as the relative scalar factor.

Finally, this distance has been divided in half to determine an approximate average distance, representing a move from a corner to the center. This approximate average plant distance, *PD,* is given by,

$$PD = \sqrt{(PL)^2 + (PW)^2} \;/\; 2 \qquad (3.2.1)$$

In a square shaped facility, the diagonal distance between opposite corners varies directly as the product of 1.414 and the square root of the area $1.414\sqrt{A}$. As the shape of the facility becomes rectangular (such as a 4 to 1) ratio, the diagonal distance is related to the area, (A), as $4.123\sqrt{A}$ (for a 4 to 1 ratio). While A is directly related to the average travel distance for similarly shaped facilities, it becomes a less valid comparative surrogate as the shapes of the facilities differ considerably. In actual plants, it is anticipated that using *PD* will work for traditionally square and rectangular facilities but that for T and X shaped facilities, shown in figure 3.4, *PD* would be a poor surrogate for average distance.

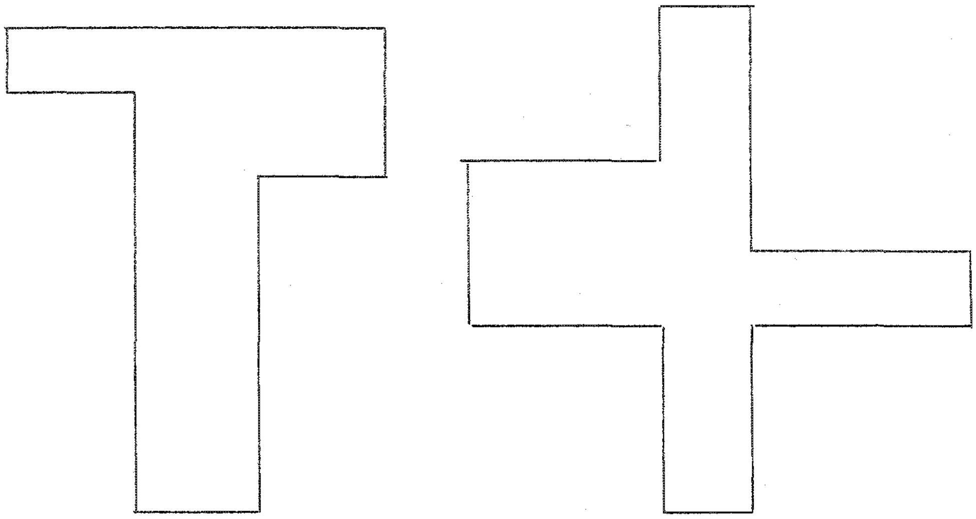


Figure 3.4. Example of T and X Shaped Facilities.

The distance component is based on path efficiency *PE* which determines how efficiently material flows through the facility. Let the layout effort, *LE*, be defined as average travel distance (*PD*) and a penalty function for the average distance deviation from the ideal efficient path (i.e., $\overline{PE}=1$). The layout effort is then given by,

$$LE = PD+(PD \times (1- \overline{PE})), \tag{3.2.2}$$

which reduces to:

$$LE = PD \times (2-\overline{PE}), \tag{3.2.3}$$

While $\overline{PE}$ can vary from 0 to 1, it should vary a small amount in practice as assembly plants have long aisles and material handling equipment that must move through those aisles in a rectilinear manner. This practical travel constraint restricts $\overline{PE}$ from becoming very close to 1, where every flow is a Euclidean distance, while common sense layout design would limit a value close to 0, where every flow would need to move several multiples of the Euclidean distance. Table 3.2 shows the minimum and maximum values for *LE* determined using (3.2.3) with a sample data set. This set, generated by a VB program, (see Appendix A) represents four different plant shapes, while keeping all other variables constant. Flow to and from the dock is both direct and cross wise flow designed facilities (i.e., Dock B and Dock A in figure 3.3, respectively).

Table 3.2. *PE* values for different sized facilities

	4-1	3-1	2-1	1-1
Direct	0.338	0.352	0.383	0.477
Crosswise	0.911	0.889	0.855	0.795
Difference	0.573	0.537	0.472	0.318

In this table, the Difference row shows a maximum practical range of $\overline{PE}$ values for facility shapes ranging from square to rectangular at a 4 to 1 ratio. As these difference ranges of from 0.318 to 0.573 represent the comparison of best and worse case situations, it is likely that actual facility ranges will be less.

Consider the example of a square 750K sqft plant ($PD = 612$) with a good $\overline{PE}$ of 0.7 and a 500K sq.ft. plant ($PD = 500$) with a poor $\overline{PE}$ of 0.5. The LE values would be similar as shown below.

$$LE = 612\ avg\ ft \times (2-0.7) = 796\ efficient\ avg\ ft$$

$$LE = 500\ avg\ ft \times (2-0.5) = 750\ efficient\ avg\ ft$$

In this example, even though the first plant is 50% larger than the second plant and has an 18% longer average distance, the efficient average distance is only 5.8% larger due to the lower efficiency in the smaller plant.

Intensity Component of Transport Effort

The intensity component of *TE* is used to measure the effectiveness of the allocation efficiency (*AE*) of parts to assembly line locations, as well as the average intensity of flow through the facility. This intensity component includes the allocation efficiency factor, average intensity per location, and the number of locations. The *AE* refers to those issues that can change over time (due to policies regarding output/day, location assignments and transport batch sizes), but are reasonably independent of the facility itself. While the dock locations and aisle locations remain fixed, the parts assigned to move between these locations (and their daily frequencies) are assignable after the facility has been constructed.

Intensity Allocation Factor

Intensity allocation is the factor that addresses the distribution of part assignments to lines and their respective frequencies of flow with respect to the popularity rule (Tompkins and White 1984). The popularity rule states that high intensity moves should be located near the docks (short distances) and low intensity moves should be assigned to the longer distances.

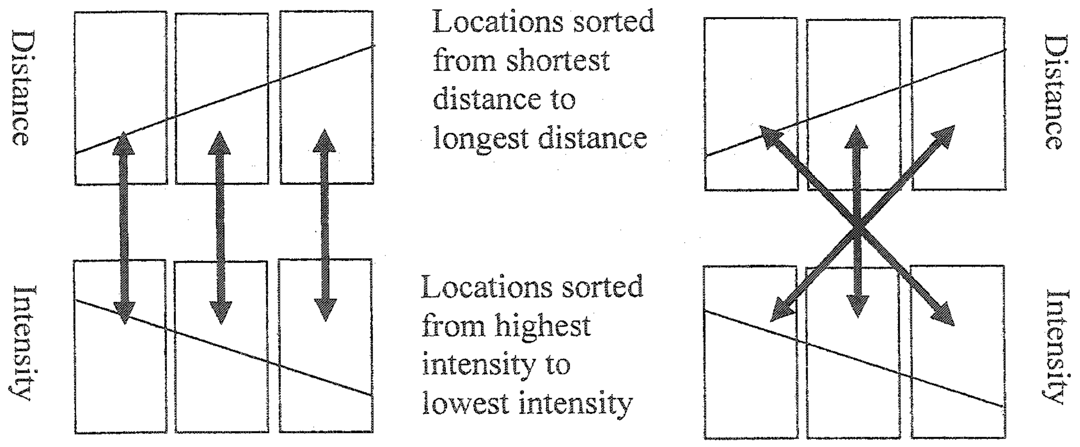
Unit load intensities are identified as the average frequency of trips taken from the dock to L_n for every part in the plant with respect to some constant time period (typically a day). Parts are delivered to line locations with 1 to many parts delivered at each location as represented by the set $P_n = \{p_{n1}, p_{n2}, p_{n3}, \ldots p_{nM}\}$ for L_n. Unit load intensities are determined by line location as the summation of the individual part intensities delivered to L_n. The location intensity for location L_n , LI_n , can be defined as

$$LI_n = \sum_{p=1}^{P} I_{p,n}\,, \tag{3.3.1}$$

where,
$I_{p,n}$ is the number of unit loads for part p at L_n per time period.

Computing intensity allocation IA requires determining the quality of the assignment of high intensity moves to short distances. The quality of assignment is determined by dividing the difference between the actual transport work TW_A and the best case transport work TW_B for the layout by the difference between the worst case transport work TW_W and the best case transport work TW_B as shown in (3.3.1). This is done in order to normalize the factor between 0 and 1. In this manner, an IA value of 0 represents a perfect assignment of high intensity moves to short distance locations and a value of 1 represents a worst case assignment in which high intensity moves are assigned to the longest distances.

(3.3.2) $IA = (TW_A - TW_B) / (TW_W - TW_B)$



Best Case IA = 0

Worst Case IA = 1

Figure 3.5. Comparison of Layout and Intensity Groups

Λ^S is a set of all location intensities in the plant to ψ^S, and is defined by,

$\Lambda^S = \{LI_1, LI_2, LI_3, \ldots, LI_N\}$ such that $LI_i \geq LI_{i+1}$

Δ^S is a set of Aisle-path distances from the dock to ψ^S.

$\Delta^S = \{d_1, d_2, d_3, \ldots, d_N\}$ such that $d_i \le d_{i+1}$

Figure 3.5 shows both the best case and worst case assignment for three locations (three locations shown for illustrative purposes only). In this manner, TW_B is determined by the summation of TW for each L_n represented in Δ^S giving

$$(3.3.3) \qquad TW_B = \sum_{n=1}^{N} d_n \times LI_n .$$

Likewise, TW_W is determined by the summation of the TW for each L_n, using Δ^S and intensities are assigned to locations in the reverse order of Δ^S such that

$$(3.3.4) \qquad TW_W = \sum_{n=1}^{N} d_n \times LI_{N-n+1} ,$$

Volume Scalar

Volume in plant-wide stock keeping unit (SKU's) loads per day, is a measure of the total intensity of flow for the plant. The total volume, V, is the summation of the daily unit load intensities for all N locations in the facility. Thus total volume, V, is given by,

$$(3.3.5) \qquad V = \sum_{n=1}^{N} LI_n ,$$

While some plants may produce a much larger variety of cars, and thus have many more SKU's delivered to the plant in smaller quantities than one which makes only one type of vehicle, it is the relative intensities of flow which are important for comparative purposes. Obviously space requirements and handling (load / unload) issues would likely be larger for the plant containing more vehicle variety, however the impact of this difference is beyond the scope of this dissertation.

A poor value for intensity allocation (a value approaching 1) indirectly describes increased traffic in the plant, as parts with higher intensities are traveling longer distances in the plant. It is logical to assume that this increased travel inefficiency (measured as allocation efficiency) would by highly related to the volume of traffic present in a perfect situation and thus would degrade (in that overall travel distance would get larger) as additional allocation inefficiency is introduced. Thus, the minimum AE value should correspond to the total volume V, reflecting no inefficiency greater than V. Likewise, the maximum AE value should incur an additional penalty of V. This additional penalty represents increased load on the system due to poor allocation, even though the volume, is not changing due to the poor allocation. Thus, using V as the baseline along with the product of V and intensity allocation IA, provides a relative measure of the dynamic aspects of intensity and volume for a particular alternative.

In this manner, plants with highly efficient intensity allocations will generate lower total relative volumes (with a lower bound of V), whereas plants with very inefficient intensity allocations will generate higher total relative volumes (with an upper bound of $2V$), as IA varies from 0 to 1. Thus, AE, expressed in relative plant-wide SKU unit loads per time period is given by,

(3.4.1) $$AE = V(1 + IA),$$

Aggregated Formulation for TE

As LE defines the relative size of the facility with respect to efficient material flow and AE defines the relative volume of efficient material flow within the facility, the product of these values would define a combined measure of the transport effort of the facility. Let transport effort, TE, be defined as the average total distance that a fixed amount of material moves over a period of time. This is similar to the original transport work formulation (2.1), but includes the penalty functions for the layout and intensity allocation. Multiplying (3.2.3) by (3.4.1) to find *TE* in unit-load-ft-sku's/day results in,

$$TE = (PD \times (2 - \overline{PE})) \times (V \times (1 + IA)) \tag{3.5.1}$$

or

$$TE = LE \times AE . \tag{3.5.2}$$

Thus *TE* represents a metric for transport effort for a facility of a certain size, production volume, aisle flow efficiency, and intensity allocation efficiency. Since the scale factors for facility size, output/day, and vehicle complexity are included, *TE* is useful for the following purposes.

1. A comparison of layout, assignment, volume and vehicle complexity changes within a facility is needed and an estimation of the degree to which those changes are likely to impact material flow.
2. Compare different facilities with respect to material handling where the material handling methods are similar and only plant size, vehicle volume and complexity, layout efficiency and allocation efficiency to determine which facility has the best performance (in terms of material handling).

Sometimes it may be desired to evaluate and compare facilities irrespective of volume and distance, such as when comparing facilities that produce vehicles in a very different manner (i.e. BMW 750il in Germany versus 50's style VW in Mexico). In these situations, the differences in the level of automation, production density(output/sqft), and unit load-based material handling equipment between those facilities are likely to bias the result with respect to average distance and unit-load volume. In these instances it is recommended to use the transport effort Factor *TEF* which does not include values for distance and volume because this metric only evaluates the material flow efficiency and allocation efficiency neither of which is likely to be biased by distance or volume. As such, *TEF* is given by,

(3.5.3) $$TEF = (2 - \overline{PE}) \times (1 + IA)\,.$$

Formulation of Transport Effort with Off-line Storage

Off-line Storage Effect on TE

While (3.5.1) is appropriate for overall layout evaluation, off-line storage locations were not considered. Off-line storage is used in assembly plants primarily because of limited storage space exists at the assembly line location for the economic order quantities (EOQ) requested for delivery to the plant. In some situations, especially those involving very high unit-load intensities, sequenced deliveries arrive to the plant from the vendor in quantities equivalent to inventory buffer sizes available at the line-side location.

EOQs represent the amount of material received from a supplier in one order (and thus stored in the plant all at once). Traditionally the EOQ is determined by the minimization of order costs and holding costs for a required annual demand of a given part. Layout designers attempt to leave as much room as possible at the line location for the storage of the EOQ for each part consumed at that location. Unfortunately, line locations containing large and bulky parts, or line locations that contain a high variety of parts (SKU's) often lack sufficient space. This overflow is delivered to and stored at, off-line storage locations.

Unit load quantities are the quantity of each part that are moved together, from either the dock to the storage area, the storage area to the line, or even the dock to the line depending upon space availability. Therefore, annual unit load frequencies for a given part will be equal to sum multiple of the number of orders per year of that part (determined by the number of unit loads required to move an EOQ of a given part). Finally, given space constraints at the line location, it is possible that the unit loads required to move an EOQ of material from the dock to the off-line storage location may be less than those unit loads required to move that same EOQ from the off-line storage area to the line (even with the same material handling device).

The use of off-line storage in assembly plants can be represented as a penalty function added to the *TE* metric as it creates additional transport effort. As off-line storage impacts both travel distance (in the selection of the storage location) and intensity (enhanced frequency of trips to the line from storage) the storage penalty function appears in both components. Finally, only locations using off-line storage should be penalized.

The presence of off-line storage can impact the direction of material flow within the layout (layout component), the intensity of flow between locations (intensity component) and the quantity of line locations that would be affected (usage).

1. Layout - Additional travel distances based on the location of Off-line storage locations relative to the line locations that they serve and the docks from which they receive material (computed via Rectilinear or Aisle methods)
2. Intensity – Potentially increased flow intensities from the storage area to the line over that of the dock to L_n (which is used as the base intensity when storage is not present)
3. Usage – Percentage of line locations using off-line storage and the distribution of these percentages over high intensity flows versus low intensity flows

Storage Indicator Variable

Let the storage indicator variable for L_n, Ω_n be defined as,

$$\Omega_n = \begin{cases} 0, & \text{if } L_n \text{ is usually supplied directly from the dock} \\ 1, & \text{if } L_n \text{ is usually supplied from storage.} \end{cases} \tag{3.7.1}$$

Layout Scale Factor

The layout scale factor will increase the average distance component, *LE*, by the additional distance imposed on flows within the plant as a result of the inclusion of off-line storage locations. As a result, plants with highly efficient off-line storage locations (with respect to dock to line material flow) will be affected much less than those with poorly located off-line storage areas. This efficiency can be determined by comparing the sum of two travel segment distances (dock to storage and storage to line), ADS_n, for L_n to the aisle based distance from the dock directly to the line. As such, the layout storage scale factor, *LSF,* is a unit-less measure of the quality of selected off-line storage locations with respect to overall material flow. LSF_n is given by,

(3.7.2) $$LSF_n = (ADS_n - d_n) \times \Omega_n \Big/ d_n \quad ,$$

where,
ADS_n is the aisle-based dock to storage to line distance, computed with the same method as d_n.

The average *LSF* over all *N* line locations defines an average plant-wide value for *LSF* that is given by,

(3.7.3) $$\overline{LSF} = \sum_{n=1}^{N} LSF_n / N \, .$$

Intensity Scale Factor

The off-line storage intensity penalty component, referred to as the intensity scale factor, *ISF*, represents the average intensity of travel increase between the off-line storage area and L_n. Most off-line storage areas receive bulk deliveries from the dock with tow-trains and other high capacity devices. Often these storage areas then supply the line in smaller unit loads which require greater intensities of travel between the storage location and the line than would have been estimated with the prior metrics between the dock and the line. On the other hand, there are situations whereby tow trains are also used between off-line storage areas and the line location and whereby travel intensities are not greater between the storage area and the line than they are between the dock and the storage area. If both intensities are approximately equal, then the analyst can simply set the intensity storage factor to 1. As shown in figure 3.6 the intensities are equivalent between the dock and L_n and between the dock and S_n.

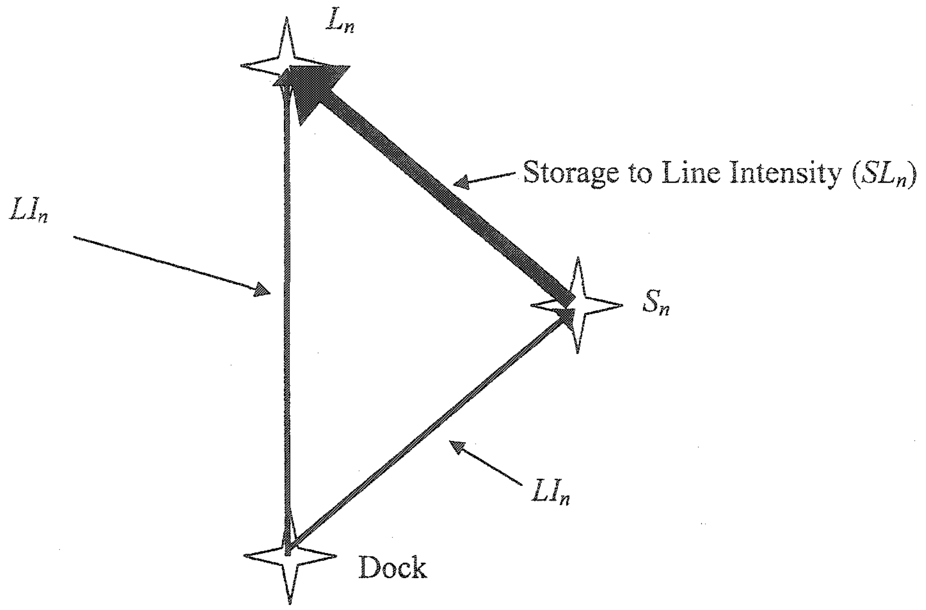


Figure 3.6. Location and Intensity Notation

Increased Storage to Line Intensity

The SLDS ratio is the fraction of moves between the off-line storage area and the line location of all moves between the dock and the off-line storage location for every location. Storage locations are obviously located somewhere between the dock location and the line location, yet often not directly along the shortest aisle-path between the two. Assuming that S_n has a symmetric distribution of locations between the dock to the line then the average would be equidistant. As such, it is necessary to only include ½ of the *SLDS* ratio when evaluating the impact that it has on the intensity along the total flow path.

Therefore, *SLDS* is given by,

(3.8.1) $$SLDS_n = (SL_n - LI_n)/(LI_n \times 2),$$

where,
SL_n is the intensity of moves between the storage location S_n and L_n, and
LI_n is the intensity of moves between the dock and $L_{n,}$ which is assumed the same as the intensity of moves between the dock and S_n

The average *ISF* is defined by,

(3.8.2) $$\overline{ISF} = \sum_{n=1}^{N} (SLDS_n \times \Omega_n) \Big/ N,$$

Total TE Formulation with Storage

As *LSF* and *ISF* both represent percentages of increased effort (relative to dock to storage effort) in the form of increased distance, or intensity as caused by storage, it is necessary to add them to 1 (representing 100%) prior to taking the product of these factors with their corresponding *LE* and AE values. Combining the layout and intensity storage factors into the *TE* formulation of (3.5.2) gives the transport effort value including storage *TES* as,

(3.9.1) $$TES = \left(LE \times \left(1 + \overline{LSF}\right)\right) \times \left(AE \times \left(1 + \overline{ISF}\right)\right),$$

Likewise the transport effort Factor *TES* (3.5.3) could also be combined with the penalty factors to give the transport effort factor with penalty *TESF* as follows.

(3.9.2) $$TESF = \left(\left(2 - \overline{PE}\right) \times \left(1 + \overline{LSF}\right)\right) \times \left(\left(1 + IA\right) \times \left(1 + \overline{ISF}\right)\right)$$

Summary of the Metric

Transport effort has been proposed as a new metric to replace transport work when evaluating and benchmarking the design of automotive assembly plants with respect to material flow. By individually identifying and isolating the distance and intensity components of transport work, the analyst can more effectively identify why plants are different instead of just how much they are different.

Two forms of the metric have been presented. The first metric, *TE* and the factor value *TEF*, is used to describe the material flow in a manner that ignores off-line storage. The second metric, known as the scalar value *TES* and the factor value *TESF*, includes off-line storage flows in the calculation of transport effort.

Both scalar and factor values are presented for each method of computing transport effort. The scalar values, *TE* and *TES* allow the analyst to evaluate and compare facilities while taking the size of the facility and the volume of flow into account. *TEF* and *TESF* allow the analyst to evaluate and compare facilities specifically with regards to aisle design efficiency and intensity allocation efficiency without biasing the evaluation with significant size and vehicle intensity or complexity issues.

It is important to be able to compare the design and use of automotive assemblies with respect to material flow in an effort to establish a basis for facility improvements or design selections. In addition, benchmarking automotive assembly plants with respect to material flow can provide an additional quantitative basis in negotiations with indirect material handling labor with respect to staff sizes, and efficiencies as well as performance pay. The development and formulation for *TE, TEF, TES* and *TESF* as well as the individual components of *PE, IA, LSF* and *ISF* provide new metrics for the plant design community as well as additional insights into quantifiable differences in plant design.

EVALUATION OF THE METRIC

Metric Evaluation Methodology

A range of plant and product configurations were used to examine the elements of *TE* as well as the composite metric. The effects of randomly assigning line locations and off-line storage locations were also studied.

Parameter Assumptions and Ranges

While an infinite range of assembly plant characteristics exist, certain parameters were fixed to reduce the number of possible values to a reasonable level.

1. The facility shapes evaluated are:
    - Square
    - Rectangular (3 to 1 ratio)
2. The facility sizes evaluated are:
    - 1 million square feet
    - 3 million square feet
3. Docks are located in the middle of one side of the facility
4. Two alternatives for dock placement are:
    - Crosswise to the aisle network (Dock A in Figure 4.1.1)
    - Direct to the aisle network. (Dock B in Figure 4.1.1)
5. Aisle spacing is uniform and there are 10 assembly lines as shown in Figure 4.1.2, which means that there are 11 aisles. Material is delivered to line locations via aisles that are in-between two assembly lines (i.e. no material delivery to the outside lines via the two outside aisles. As such, those aisles are only provided for spacing purposes to position the assembly lines within the facility). On odd aisles, the actual material flow would be going through

the middle of the assembly line, as it would be necessary to move past the assembly line, go down the next aisle and then backtrack into the assembly line to model the move correctly. This simplification was chosen because it was not deemed material enough to justify the additional complexity to the model to handle these moves realistically.

6. A total of 25 locations are spaced at fixed intervals along each assembly line in a lattice configuration as shown in Figure 4.1.2. These locations are used to represent line locations L_n and the storage locations S_n.
7. Storage locations S_n are:
   - Randomly located at a location lattice point in the same aisle as the line location (best case)
   - 100 percent randomly located among any location in the plant (worst case)
   - or co-located at a line location.
8. Storage percentages are:
   - 0%, 50%, or 100%
9. Aisles are not blocked at the end (no aisle end-caps)
10. Volume is evaluated at:
    - 1000, or 3000

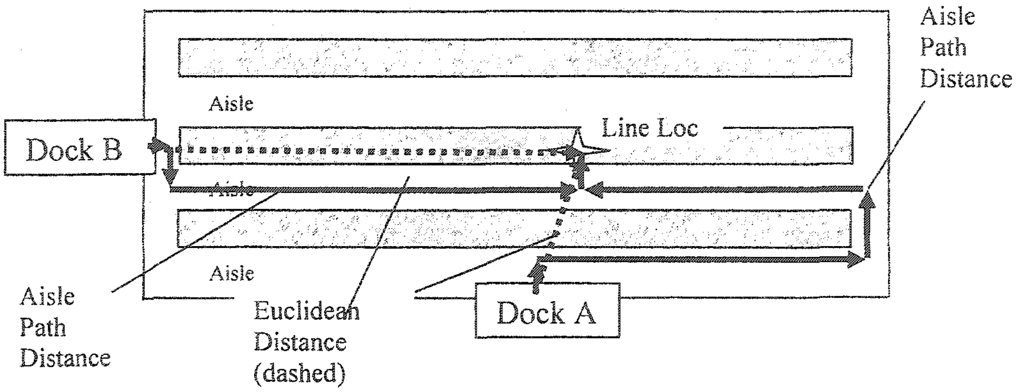


Figure 4.1.1. Example of Test Plant Flows

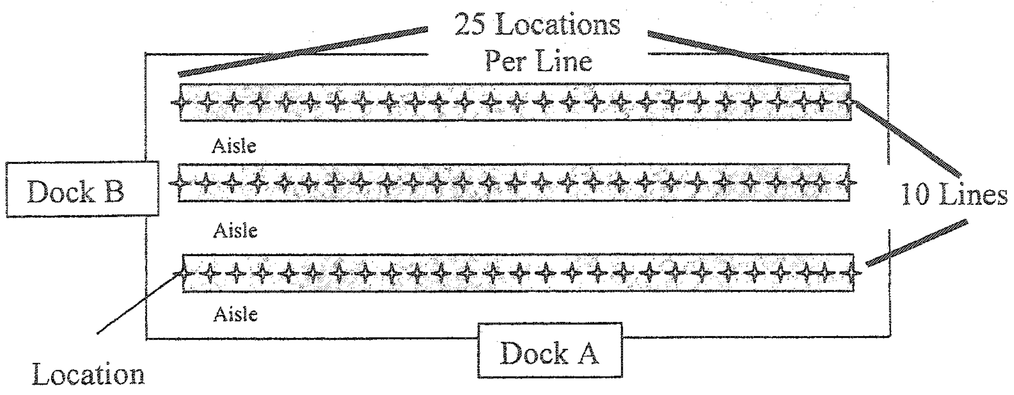


Figure 4.1.2. Example of Test Plant Locations

Experimental Method

Given the large number of parameters to be evaluated and the potential for parameter interaction, the *LE* and *AE* parameters were evaluated individually. In each case, the values for *TE* and the *TES* are presented (both with and without off-line storage) and are compared to the classical *TW* value for Aisle-based distances. In this manner, it is possible to study the ability of *LE* and *AE* to describe specific attributes of layouts corresponding to changes in the input parameters.

Layout Parameters

The plant related parameters that are likely to affect the layout metrics include the plant's size, shape and dock position. As such, each of these values is changed individually to determine its impact on *LE,* as well as *TE,* with a constant value for both plant volume and a specific proximity method.

For the evaluation of *LE,* volume was 1,000 and the intensity distribution was generated using a linear function with a maximum intensity of 1,000 and a minimum intensity of 0, allocated over the 250 line locations.

Dock positions A and B were used to evaluate cross-wise flows and direct flows, respectively. Direct flows are indicated by a 'D' in the dock column of the table, whereas crosswise flows are indicated by an 'X' in that column.

For Table 4.2, eight data sets were generated by a computer program (shown in appendix A) that allows the user to specify a set of input parameters and then compute the results of both transport work, transport effort and the various transport effort parameters. As the data sets in Table 4.2 do not contain any randomness, the specification of the random seed value to generate the results shown is irrelevant.

Table 4.1. Fixed Parameters Table

Proximity	Lines	Loc	Tot Loc	Volume
Linear	10	25	250	1000

Table 4.2. Results of Layout Parameters Experiment of Metric

Set	Dock	PD	$\overline{PE}$	LE	TE	TW	TEF
1	D	707	0.795	852.1	106507959	68738309	1.205
2	D	913	0.889	1014.1	126763914	89543577	1.111
3	D	1225	0.795	1475.8	184471785	119054751	1.205
4	D	1581	0.889	1756.6	219580655	155114106	1.111
5	X	707	0.477	1076.9	134615453	131545864	1.523
6	X	913	0.352	1504.3	188035041	172057172	1.648
7	X	1225	0.477	1865.2	233153965	227837436	1.523
8	X	1581	0.352	2605.7	325714599	298051104	1.648

Table 4.3. Lengths and Widths for PD

Length	Width	PD
1000	1000	707
1732	577	913
1732	1732	1225
3000	1000	1581

For data sets 1 and 2, the plant was changed from square (data set 1) to rectangular (data set 2) with a length to width ratio of 3 to 1. This was also done for data sets 3 (square) and 4 (rectangular) where the size was also changed from the 1 million square feet (used in data sets 1 and 2) to 3 million square feet. Each of these changes produced a different *PD* value as shown in Table 4.3.

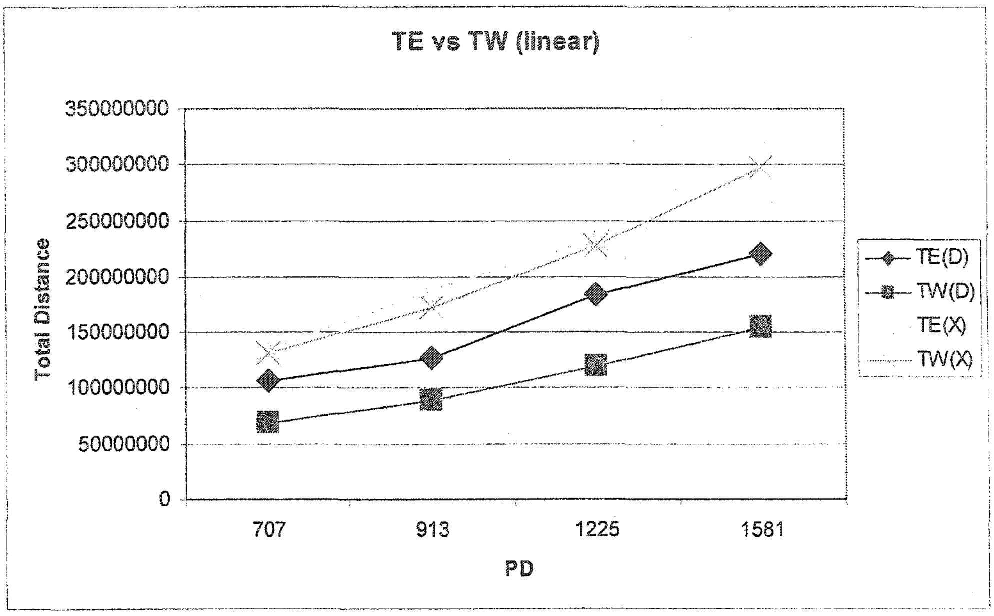


Figure 4.2.1. Transport Effort Versus Transport Work

Figure 4.2.1 compares transport effort and transport work, which demonstrates that *TE* and *TW* track fairly closely, and indicates that the aggregation of the individual *TE* parameters into the overall *TE* metric is fairly representative of the overall value for *TW*. The sets were purposely sequenced such that the effort and work would increase.

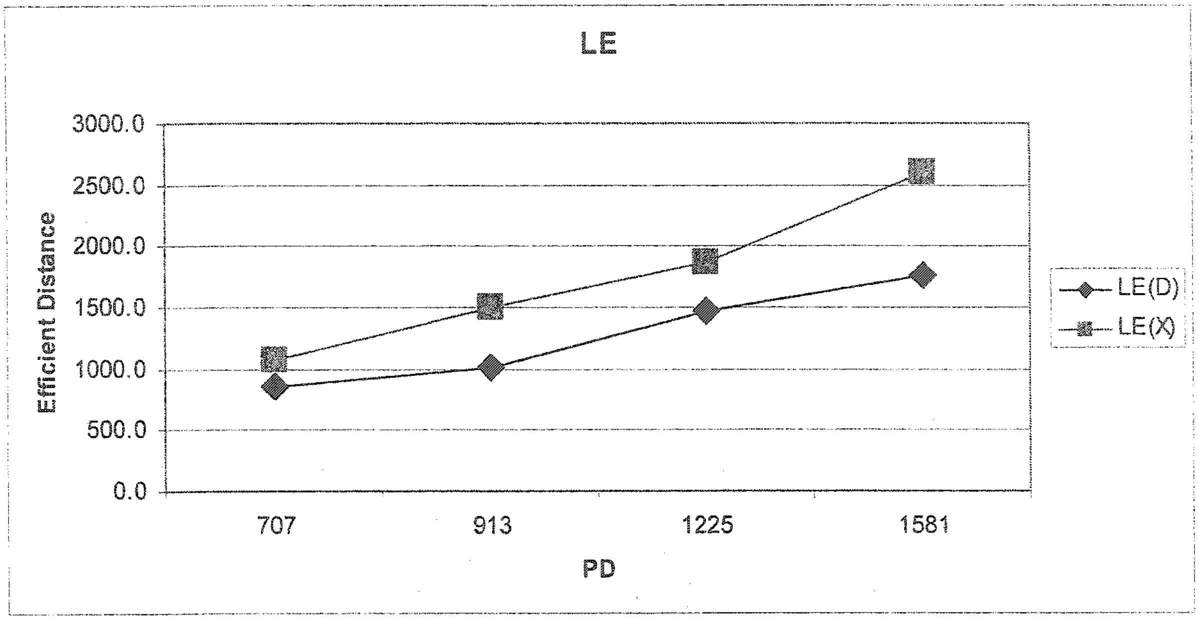


Figure 4.2.2. Layout Component (*LE*) of Transport effort

Figure 4.2.2 is a graph of *LE* and is nearly identical in shape to that of *TE* shown in figure 4.2.1, as expected, since the parameters likely to affect *AE* were held constant for the sets. Distances are noticeably larger for *PD* values of 913 and 1581, which represent rectangular plants, than their corresponding *PD* values of 707 and 1225 which represent square plants of the same size respectively. This difference is caused by the fact that a rectangularly shaped plant negatively affects *LE* more than a square plant, holding size equal. This is shown when the average values for *PD* between both plant shapes for the smaller plant versus those shapes for the larger plant is tripled in size, a 73% increase in the average *PD* was noticed.. The same increase was observed when comparing distances for *LE(X)* and *LE(D)*, indicating that direct and crosswise flows are equally impacted by increases in plant size.

When considering plant shape, the impact of crosswise flows was more pronounced than with direct flows. This is seen in the 40% increase in the average distance in *LE(X)* from the *PD* values 707 and 913 to that of *PD* values 1225 and 1581, where an increase of only 20% was noted for *LE(D)* from *PD* values 707 and 913 to *PD* values 1225 and 1581.

Therefore, it is evident that the impact of plant shape is considerably more important to crosswise flows than it is for direct flows. This increased shape importance for crosswise flows is expected because as the size increases, so does the length, and thus more backtracking would be incurred by a cross-wise flow positioned dock that would not be present for the direct-flow positioned dock. In summary, it appears that *LE* is amplifying the effects of cross-wise and inefficient material flow over that of the classical *TW* metric, and thus while *TE* is comparable to *TW* it does possess some unique behaviors, just as desired.

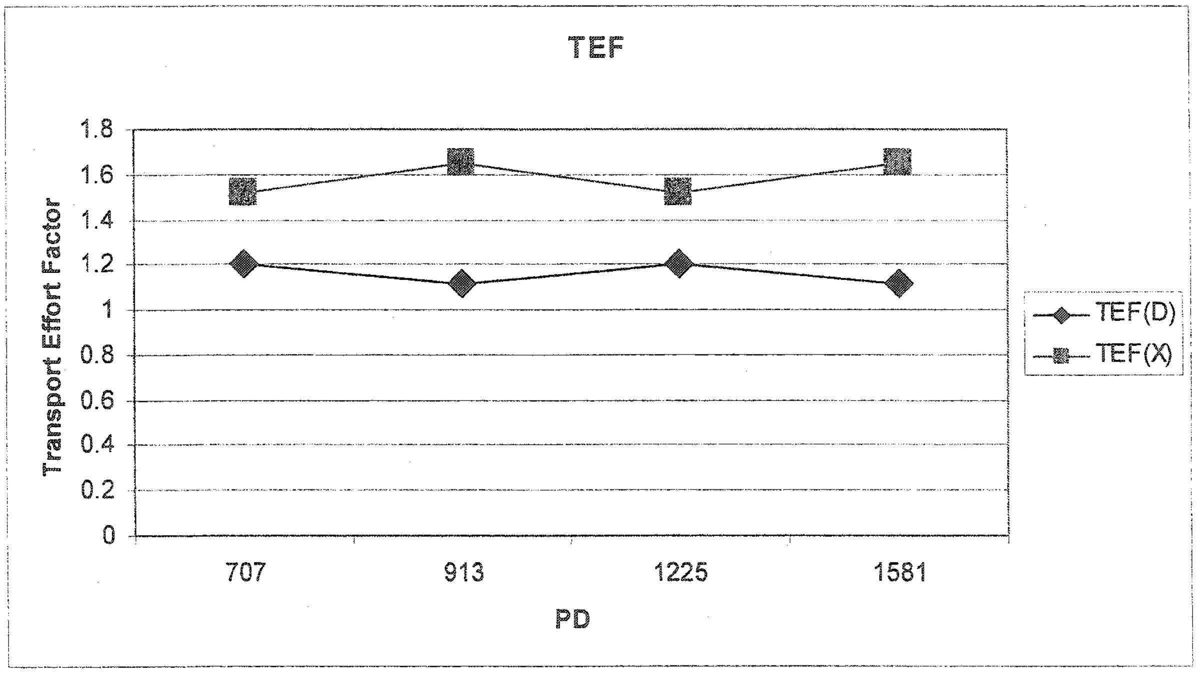


Figure 4.2.3. Transport Effort Factor

Figure 4.2.3 is a graph of the transport effort factor *TEF* which does not include the values of volume or distance. This graph clearly shows the increased total distance of crosswise flows used in *TEF(X)* versus the direct flows used in *TEF(D)*. In addition, this figure clearly shows the inverse relationship between *TEF(X)* and *TEF(D)* caused by long facilities (*PD* of 913 and 1581) versus that of square facilities (*PD* of 707 and 1225). In this example *TEF(X)* is 8.5% greater for long facilities than it is for square facilities, whereby

TEF(D) is 8.2% less for long facilities than it is for square facilities. Notice that since the size of the facility is not a parameter in *TEF*, then the inefficiency of plant shape is independent from its size.

Intensity Allocation Parameters

The plant related parameters that may contribute to the intensity allocation include the intensity distribution (i.e. Weibull or linear function – not to be confused with the pdf) used to allocate intensity to locations within the plant as well as possibly the direct or crosswise flow placement of docks in the plant. As such, each of these values is changed individually to determine its impact on the *AE*, as well as *TE* when given a constant value for plant size and shape. For the evaluation of *AE*, the plant size has been set to 1 million square feet and the shape has been set to square. A discrete uniform distribution was used to select intensity.

The intensity distribution was generated with both a linear and a Weibull function. The linear distribution is defined such that maximum intensity is equal to volume and minimum intensity is always 0. The Weibull distribution file for 250 locations, used by the program, is located in Appendix B.

A linear distribution was chosen as a way to control the intensity to line locations from the maximum volume to zero volume. Figure 4.1.3 is an actual allocation of intensity to line locations for an American automotive assembly plant, which shows a very non-linear distribution. In this figure, the X-axis represents the relative amount of unit loads that correspond to the relative amount of SKU's per plant. Thus, from this figure it can be seen that approximately 80% of the unit load intensity in the plant corresponds to approximately 15% of the SKU's that are likely delivered to individual line locations. Because most of the flows are located towards the low end, a Wiebull function was chosen due to its ability to represent a shape with very high initial intensities as well as very low and mid-to-low range intensities.

Random intensities are assigned to locations by starting with LI_1, in the Λ^s set of location intensities (sorted from the highest to lowest), while the Aisle-path location distances d_n are located in the set D^s (sorted from shortest to longest). Random intensities are assigned to locations by incrementing n by 10, 4 and 2 for 10%, 25% and 50% random assignment, respectively. Locations in Λ^s not selected for random assignment are assigned the next unused intensity in the distribution (either linear or Weibull) of intensities (sorted from high to low). This is to ensure that an intensity can be only used once (i.e. without replacement).

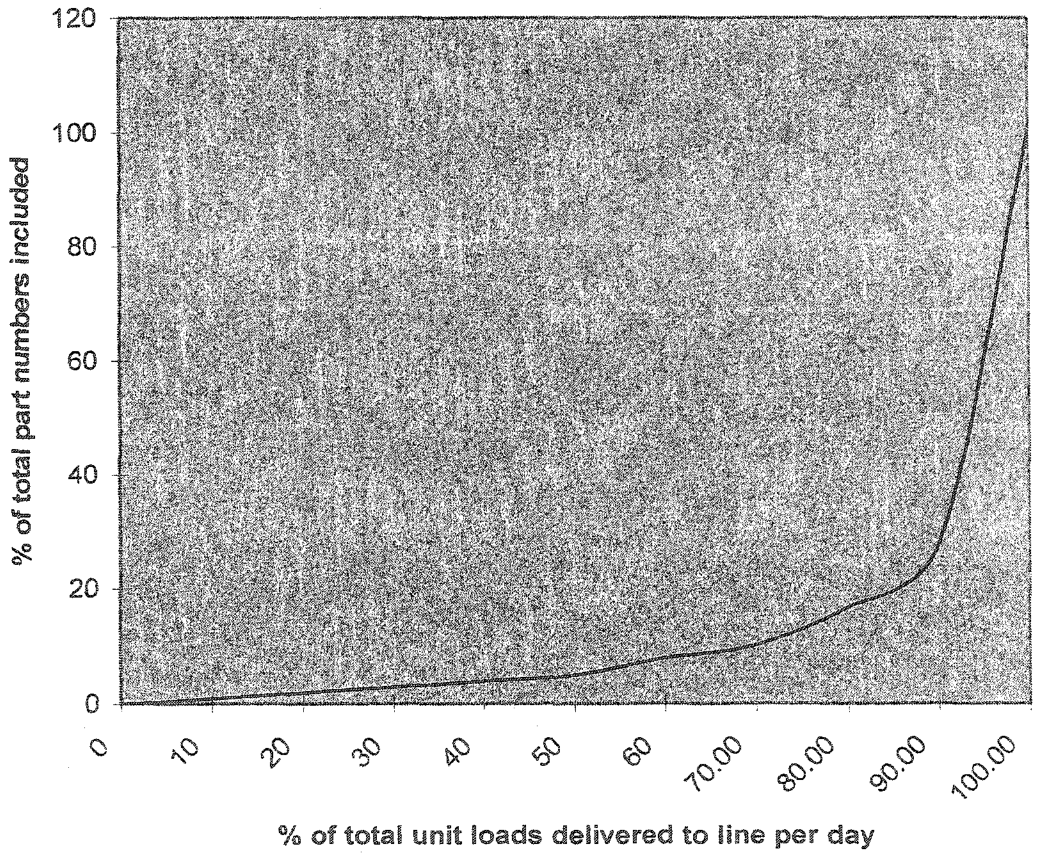


Figure 4.2.4. Actual Distribution of Intensity to Line Locations

The random assignment method addresses the way flow intensity (LI_n) is allocated to the line locations (L_n). In the 0% Random method, the highest intensities are allocated to the shortest distances in a linear fashion. As a result, the 0% Random method generates a perfect allocation and thus an *IA* factor value of 0. The four other methods, allocate the intensities to a percentage of the locations in the plant on a random basis. As such, a random method used for 10% of the locations allocates a random intensity value based on the user-specified allocation (i.e. Weibull or linear), while the remaining locations are assigned a linearly defined intensity according to the linear function discussed in the prior section.

For Table 4.5, 10 data sets were generated by a computer program (shown in appendix A). Each of these data sets was generated from 10 runs using different random number seeds, thus the values in this table are the means of the 10 replications. The program allows the user to specify a set of input parameters and ten random number seed values and then computes the average results of both transport work, transport effort and the various transport effort parameters. The random number generator provided in VB.NET was used to randomly assign intensity to locations to a percentage of the locations not allocated via the popularity rule according to the linear and Weibull intensity functions. A sensitivity analysis based on the random values is provided in a subsequent section of this chapter.

Table 4.4. Fixed Parameters Table

Length	Width	Area	Aisles	Loc	Tot Loc	Volume
1000	1000	1000000	10	25	250	1000

Table 4.5. Results of Allocation Parameters Experiment of Metric

Set	Dock	% Rand	PE	IA	LE	AE	TE	TW	TEF
1	D	0	0.795	0.000	852	125000	106491875	68738309	0.205
2	D	10	0.795	0.037	852	129605	110415152	70353094	0.225
3	D	25	0.795	0.085	852	135600	115522555	72455254	0.242
4	D	50	0.795	0.186	852	148268	126314580	76897153	0.284
5	D	100	0.795	0.477	852	184641	157302096	89651330	0.330
6	X	0	0.477	0.000	1077	125000	134595125	131545864	0.523
7	X	10	0.477	0.031	1077	128856	138747273	132839844	0.563
8	X	25	0.477	0.073	1077	134091	144383634	134596364	0.615
9	X	50	0.477	0.157	1077	144638	155740928	138135762	0.715
10	X	100	0.477	0.411	1077	176350	189887266	148777160	0.826

Table 4.6. Ratio of 95% Confidence Interval to Mean

Set	Dock	% Rand	IA	TE	TW
1	D	0	0.00%	0.00%	0.00%
2	D	10	12.65%	0.45%	0.29%
3	D	25	10.24%	0.80%	0.53%
4	D	50	5.35%	0.84%	0.57%
5	D	100	3.66%	1.18%	0.85%
6	X	0	0.00%	0.00%	0.00%
7	X	10	17.96%	0.54%	0.17%
8	X	25	8.31%	0.56%	0.19%
9	X	50	4.28%	0.58%	0.20%
10	X	100	3.71%	1.08%	0.43%

The first 5 data sets were generated with the direct flow dock position, noted with the D in the Dock field of Table 4.5. For the first 5 data sets, the intensity allocation was progressively generated from a perfect linear assignment to an imperfect random assignment (not to be confused with a worst possible assignment). The next 5 data sets were generated to start from a perfect linear assignment to an imperfect random assignment using the cross-flow dock position.

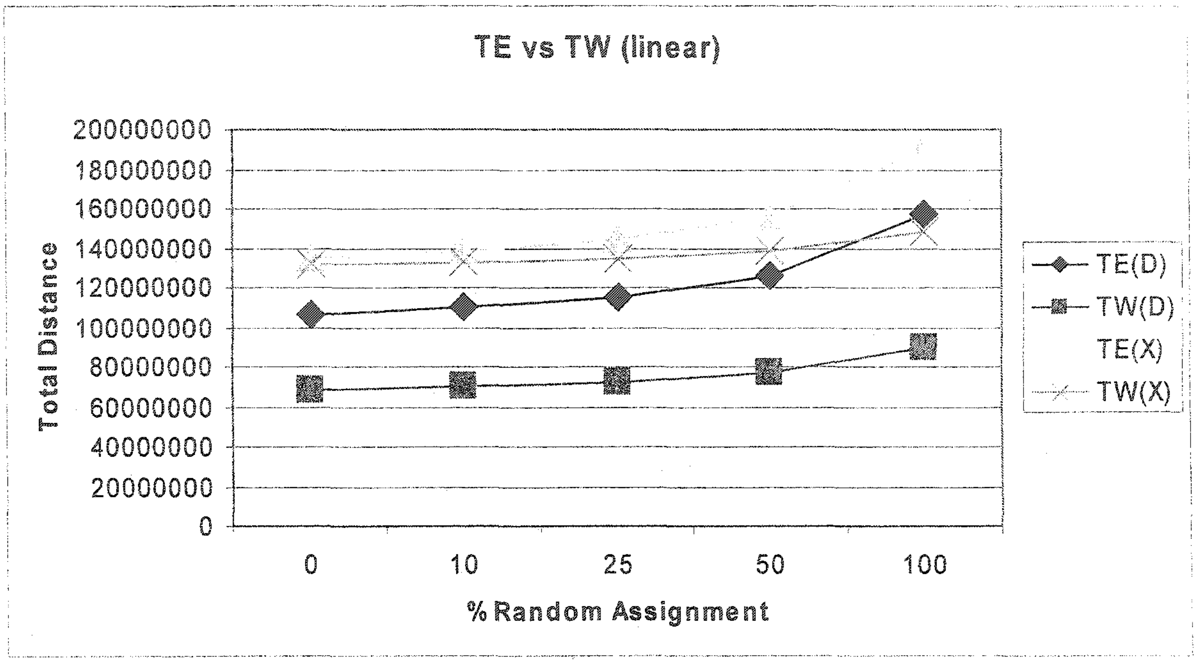


Figure 4.3.1. Transport Effort Versus Transport Work

Figure 4.3.1 shows the graph of *TE* versus *TW* which clearly demonstrates that *TE* is more sensitive than *TW* to the inefficient allocation of intensity (i.e. random assignments approaching 100%). The sets were purposely sequenced such that the effort and work would increase as the randomness is increased from 0 to 100%. Given the uniform manner in which random intensity assignments are introduced, coupled with the fact that the values reported in Figure 4.3.1 are the means from 10 different replications, it is likely that intensity allocations with increased randomness will be worse.

It appears, from Figure 4.3.1, that the difference between *TW* and *TE* for direct-flows is much greater than for crosswise-flows indicating that as the layout flow efficiency becomes better, the *TE* becomes even more sensitive which is exactly what would be desired in such a metric.

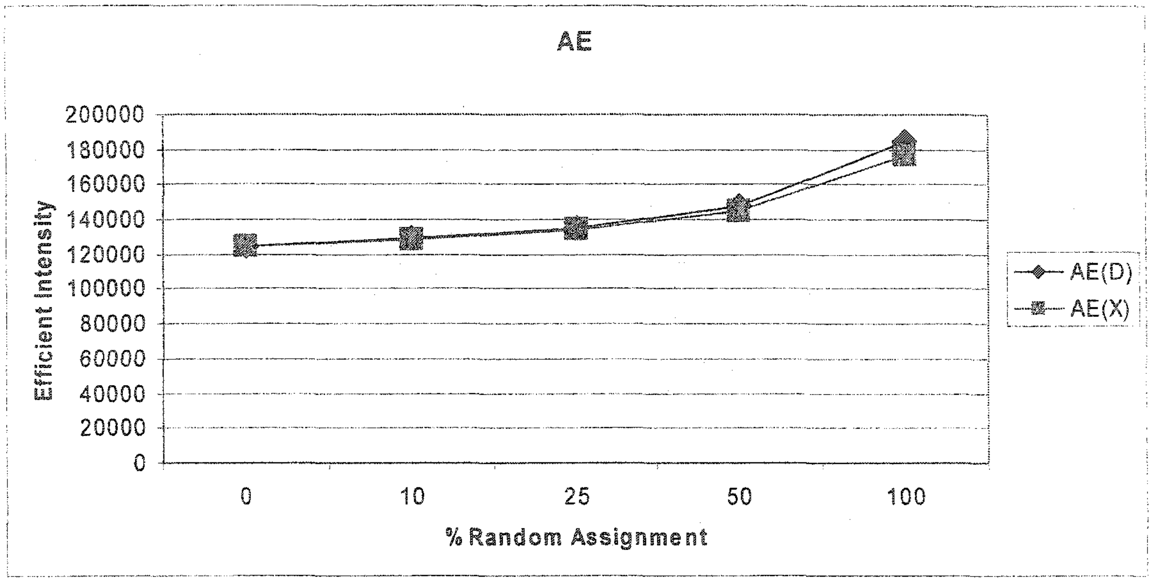


Figure 4.3.2. Allocation Component (*AE*) of Transport effort

In figure 4.3.2 the *AE* portion of *TE* clearly shows the increasing work effort caused by the increasing inefficiency of *IA*. As expected, *AE* is independent to the position of the docks and the flow path inefficiency as there is a minimal perceived difference between the direct flow and crosswise flow data sets.

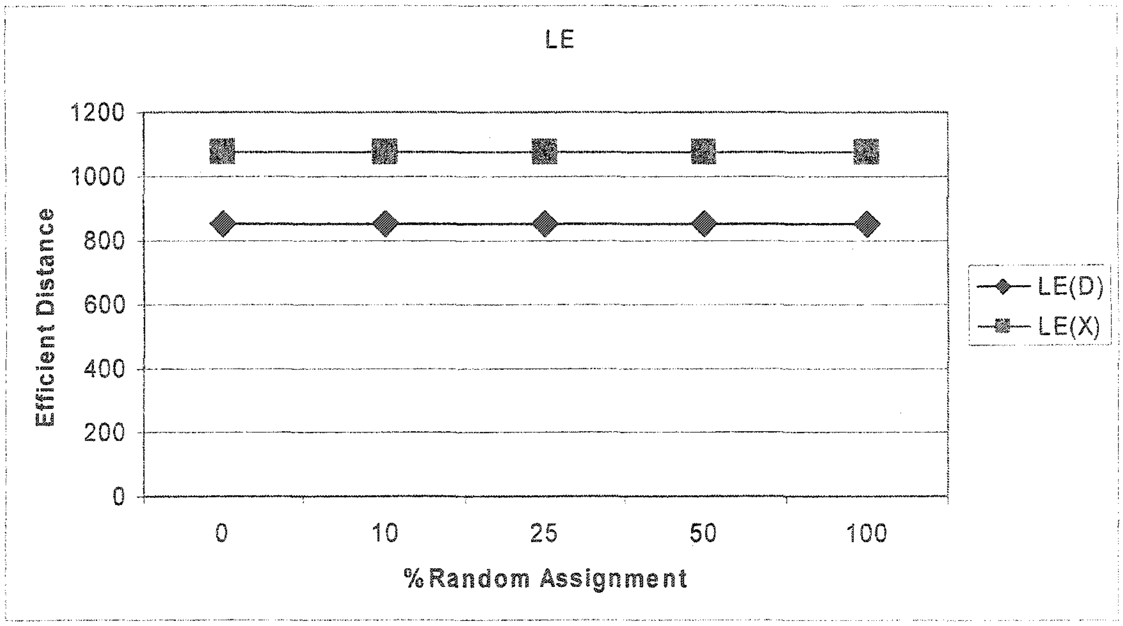


Figure 4.3.3. Layout Component (*LE*) of Transport Effort

Figure 4.3.3 clearly demonstrates how the *LE* of *TE* isolates the impact of flow efficiency as the direct flow dock placement is clearly different to that of the cross-flow dock placement. It also appears that *LE* is independent of any *IA* variations as no variation is seen within either the direct or cross wise flow values.

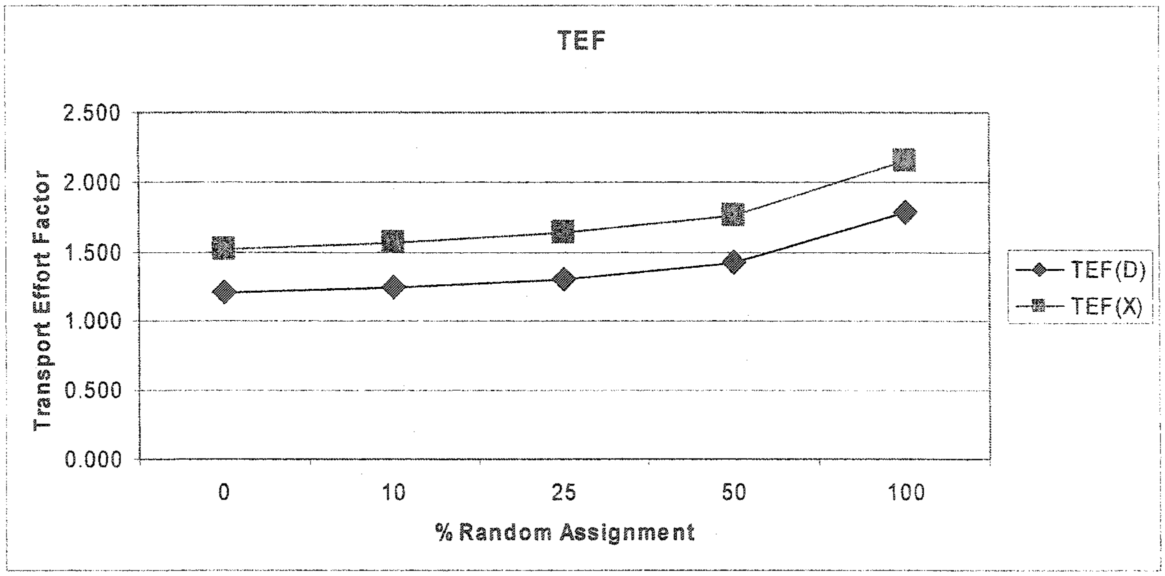


Figure 4.3.4. Transport Effort Factor

Figure 4.3.4 demonstrates how combining the *IA* with the $\overline{PE}$ in *TEF* generate a trend line that clearly shows the layout becoming increasingly inefficient as the randomness of the intensity allocations is increased and then eventually combined with the impact of cross-wise flow from the docks. As the *TEF* figure 4.3.4 is computed without the values of volume and distance that were held constant at the value 125000 trips and 707 feet respectively, it is not coincidental that the graphs of *TEF* and *TE* would be nearly identical.

Evaluation of Randomness

The only random element in this study is the assignment of intensity to locations in the 10%, 25%, 50% and 100% random data sets. Ten data sets were generated (using different random number seeds) for each of the four random percentages for both direct and crosswise flows. The mean, standard deviation and 95% confidence interval, were generated and reported for each data set, as indicated in the aforementioned figures and tables. An example from the 100% random data set, which is likely to contain the greatest variability due to the random number generator is shown in Table 4.7. It can be seen that the results vary around 0.7% about the mean for every standard deviation. Thus there exists a 95% probability that the mean is within the interval according to $148772795 \pm 1.96 \times 1055584/\sqrt{10}$ (i.e. 100% random versus 10% random). Therefore, the impact of randomness on the results of this study overall have not been significantly large. Each of the data sets used so far in this study were evaluated using the same method.

Table 4.7. Randomness Evaluation TW

	TW
Set 1	148914806
Set 2	149071570
Set 3	149605874
Set 4	148704791
Set 5	148389382
Set 6	147677103
Set 7	146817375
Set 8	149143128
Set 9	150747232
Set 10	148656688
Average	148772795
Std Deviation	1055584

Evaluation of Volume Differences

In order to determine the potential impact on significant volume differences to the comparative results generated by both *TE* and *TW*, data sets were made with plant volume of 2 and a plant volume of 100 using a Weibull distribution, holding everything else constant. Figures 4.4.1 and 4.4.2 clearly show that significantly different volumes do not generate any perceivable difference when comparing *TE* to *TW* or even *TE* to *TE* and *TW* to *TW* with obvious exception being the magnitude of the total distances. However, the difference between D and X configurations is larger for TW than TE.

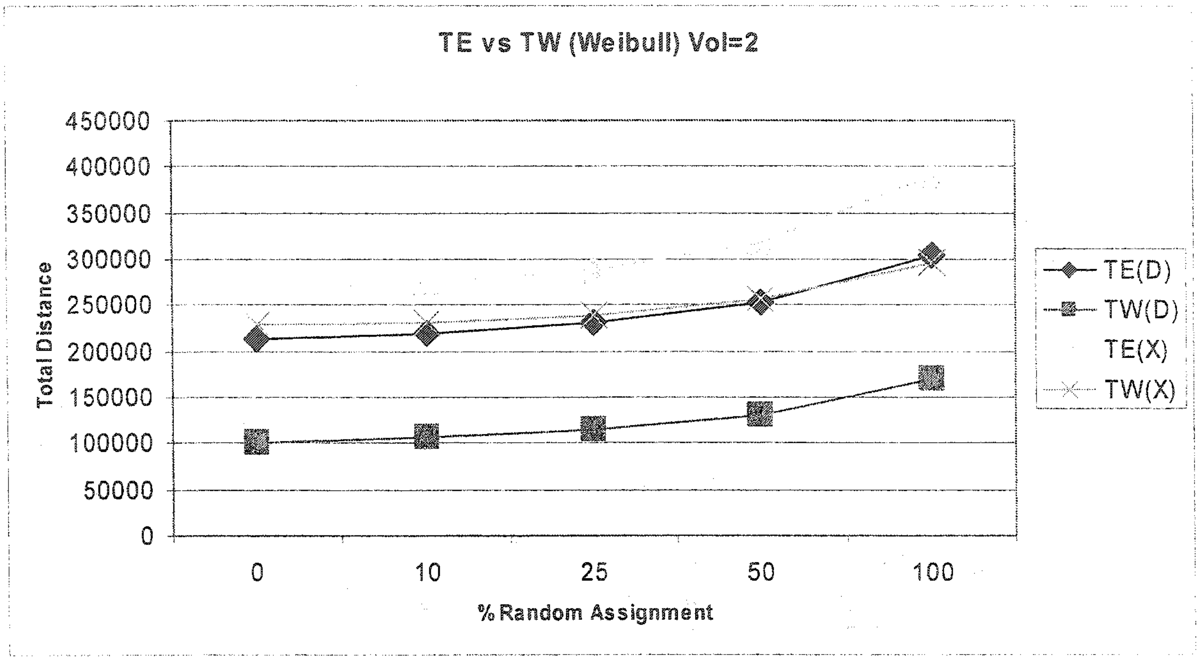


Figure 4.4.1. Low Volume Transport Effort vs Transport Work

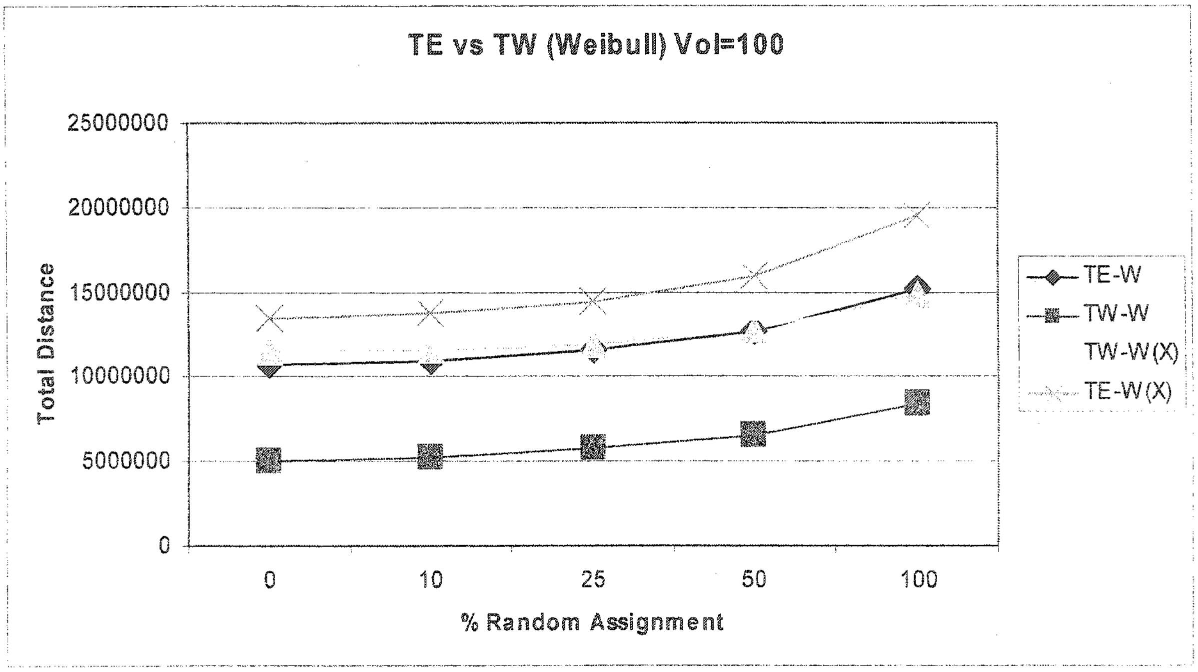


Figure 4.4.2. High Volume Transport Effort vs Transport Work

Evaluation of Intensity Distribution

It is likely that the allocation of intensity to locations within the plant will differ from one facility to another. In order to determine the impact on the results of different intensity allocations within the plants, program runs were made with both a linear (max=1000, min=0, for locations=250) and a Weibull (alpha=1, beta=53 for locations=250) intensity functions. The Weibull function was selected because of its parameter flexibility to easily generate different shapes. The Weibull alpha and beta values were selected such that the curvature of the distribution was visually maximized. In both cases, the total intensity within the facility volume, *V*, was held constant. As such, the Weibull contains higher intensities at both ends of the allocation, and a lower intensity for the middle portion of the allocation. Figure 4.5.1 shows a diagram of the intensity allocation for the maximum location intensity equal to 1000 (linear) and plant volume, *V*, equal to 125,000 (250 locations with an average intensity of 500).

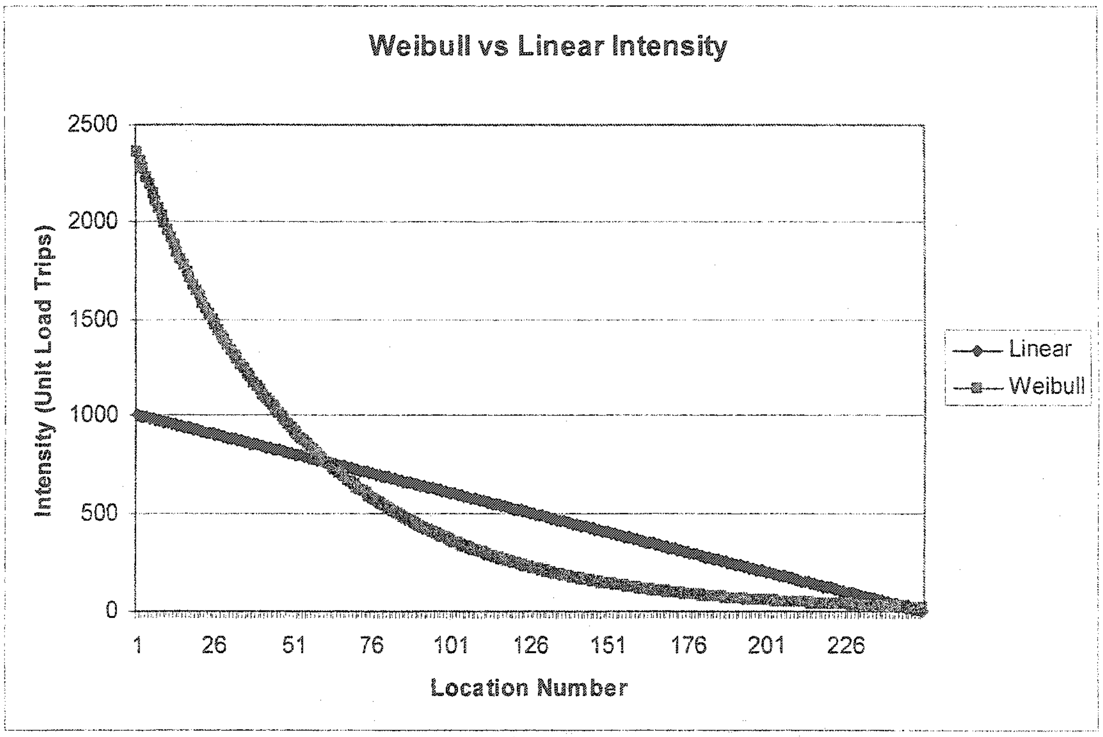


Figure 4.5.1. Weibull vs Linear Intensity Distributions (Vol = 100)

Figures 4.5.2 and 4.5.3 clearly shows that *TE* is barely affected by differences in the intensity distribution between alternatives, and that *TW* is much more impacted by as much as 27% (different of Weibull over linear) and this impact is more pronounced at perfect intensity allocations and goes to nearly zero at random intensity allocations.

The increased total distance range in *TW-W* (Weibull) over that of *TW-L* (linear) is caused by the increased magnitude of intensity (up to 2.5 times) for the first 20% of the locations in the Weibull distribution as compared to the linear distribution. In a perfect assignment, this much higher intensity is multiplied over the shortest 20% of distances, while reducing the intensity multiplied over the remaining 80% of longer distances. As the intensity differences among locations is much less variable over the linear distribution, as seen with *TW-L* in Figures 4.5.2 and 4.5.3, then it becomes less sensitive to random assignment impacts than does *TW-W*. Therefore, at a total random assignment, this difference disappears and the two values become practically the same.

This same effect is not seen in *TE*, meaning that comparisons using *TE* will not be subject to a bias caused by intensity distribution differences. As a result, the range of total distance for both *TE-W* (45%) and *TE-L* (40%) is similar to that of *TW-W* (30%). *TE-L* (40%) has a much larger range than *TW-L* (12%), because distances are constant for all locations with *TE* and thus only intensity is changing. For *TW*, distances to locations change inversely to intensity at those locations which reduces the range of total distance in *TW* as opposed to *TE*. Therefore, since *TE* is a total of the intensity at all locations, the distribution of the intensity becomes irrelevant provided that the total volume of the intensity between comparisons is the same.

This effect is not what would be desired when using *TW* for comparisons on plants that have good *IA* values but different intensity distributions. As such, *TE* would make for a more accurate comparison metric versus *TW* with regard to situations where intensity allocations are likely to differ.

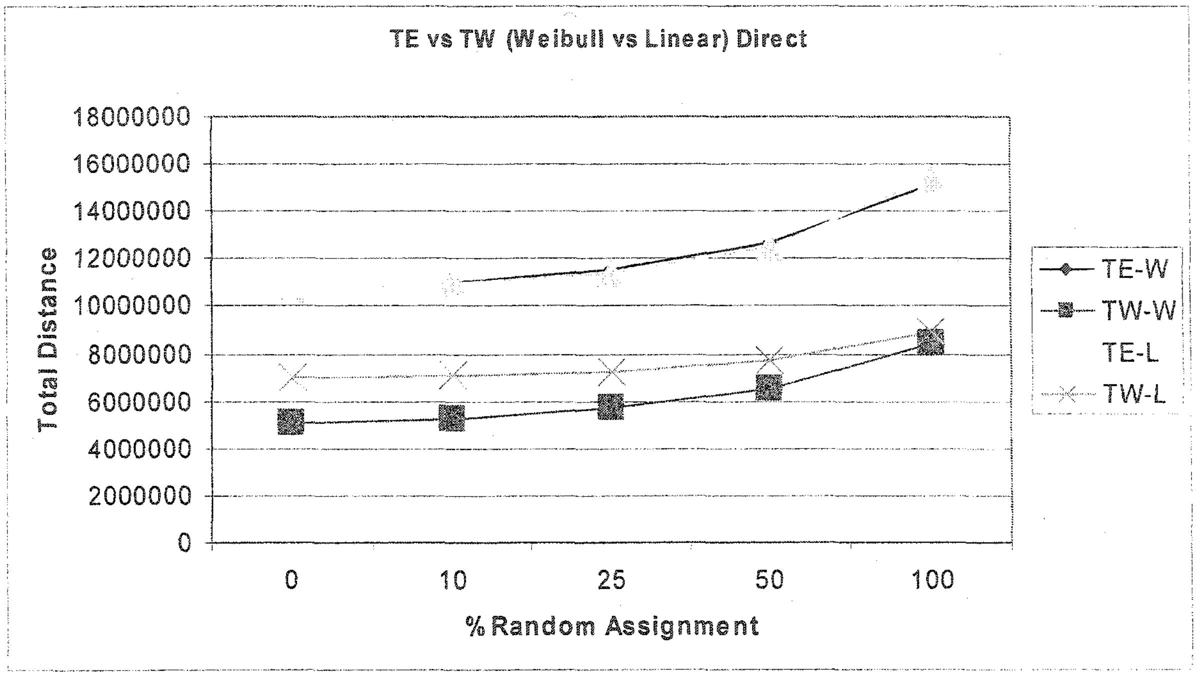


Figure 4.5.2. TE & TW Weibull vs Linear Comparison (direct)

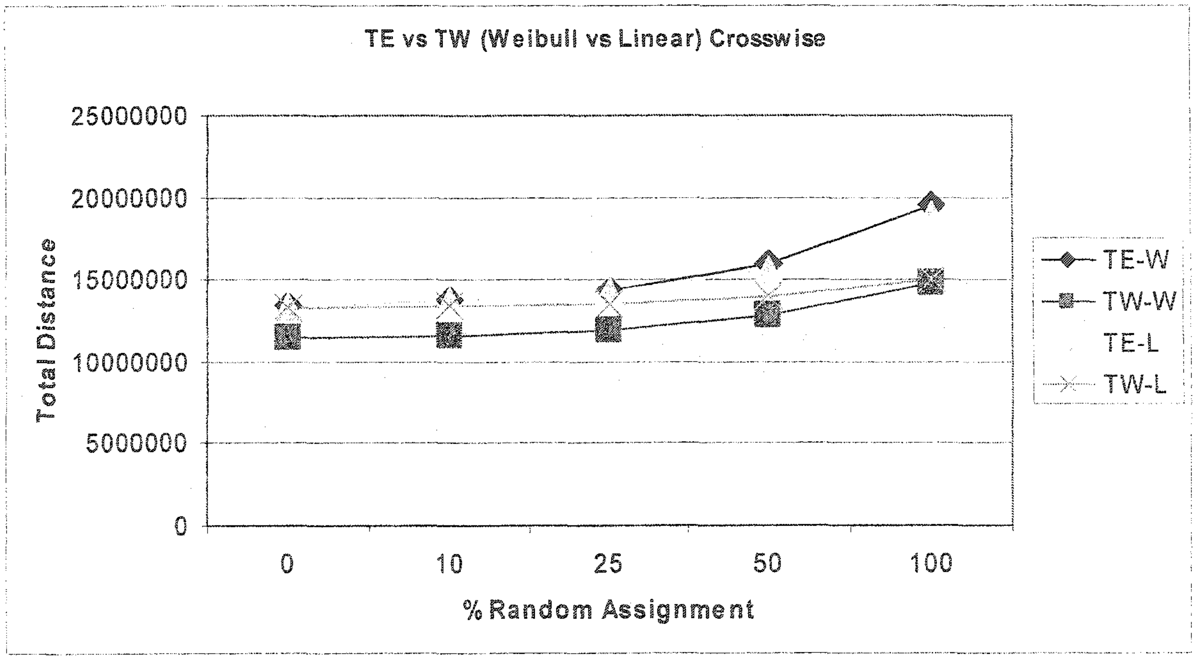


Figure 4.5.3. TE & TW Weibull vs Linear Comparison (crosswise)

Layout Parameter with Storage Factor

It is interesting that *TW*, in Figure 4.6.1, shows a relatively constant amount of work for each of the direct and crosswise flows whereas *TES* continues to present the increased inefficiency within those runs. In this manner, *TES* is amplifying the internal error within the direct and crosswise configurations that *TW* is masking. In addition, when limiting the random assignment of off-line storage to within the aisle as opposed to anywhere in the facility, *TES* is impacted much more greatly for direct flows than it is for crosswise flows. Again, this differentiated impact can be attributed to the lower base distance value of direct flows than for crosswise flows.

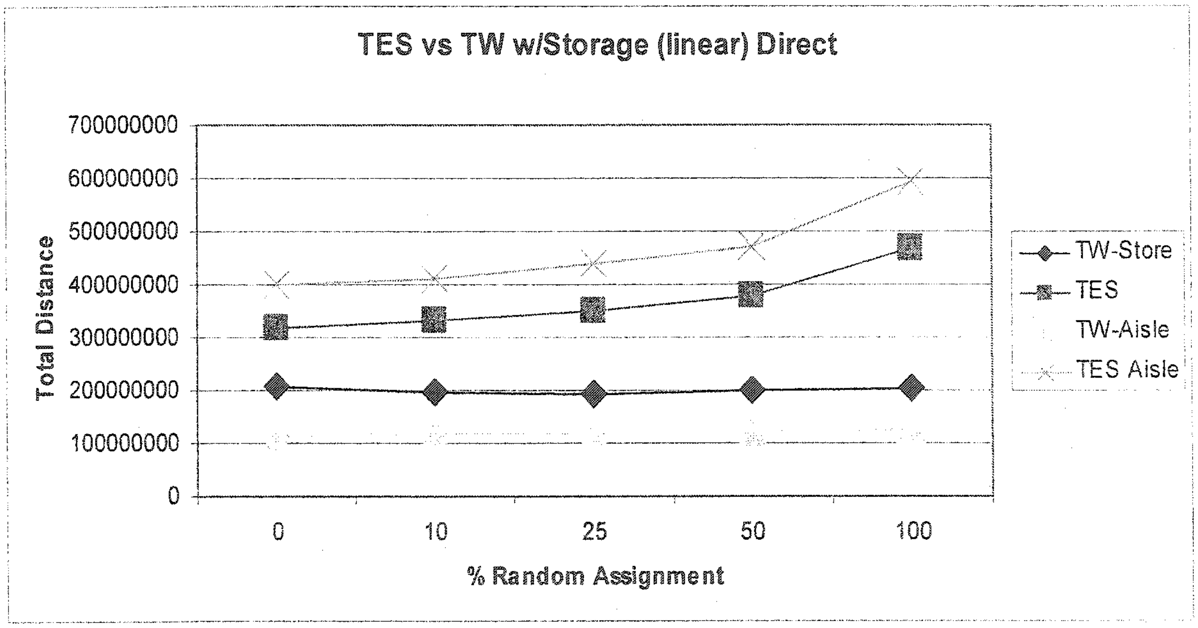


Figure 4.6.1. TES & TW w/storage Comparison (direct)

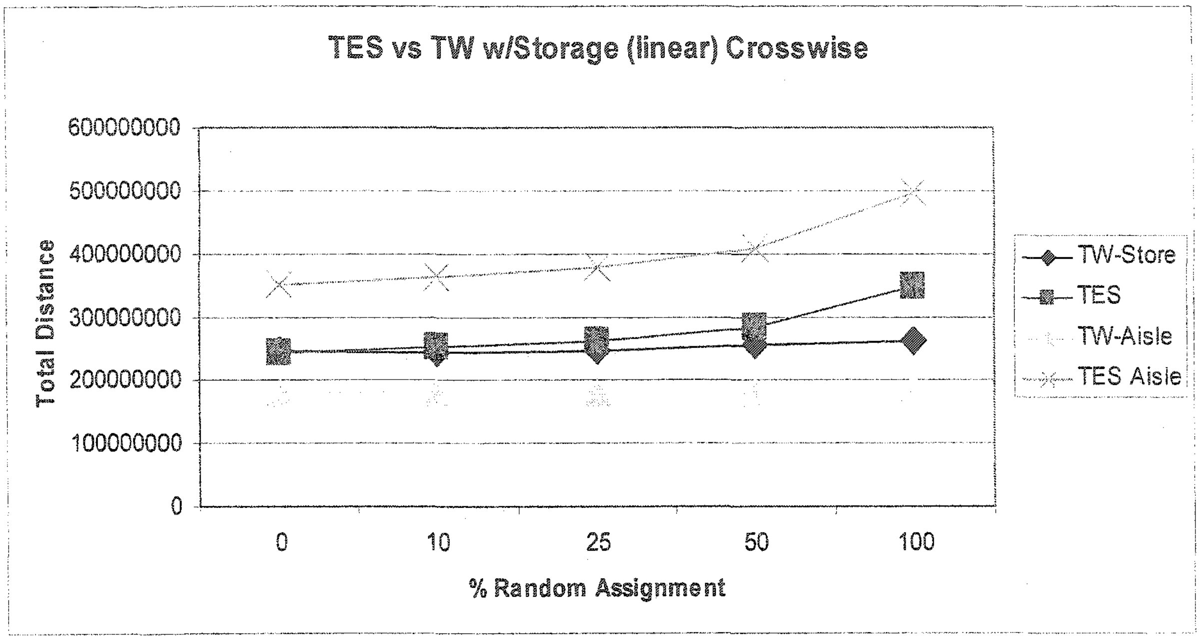


Figure 4.6.2. TES & TW w/storage Comparison (crosswise)

Introducing *LSF* to the model in an effort to evaluate the impact of off-line storage generates the impact seen in Figure 4.6.3. It can be seen that *LSF* varies between the direct flows and the crosswise flows with both incorporating randomly assigned off-line storage to 100% of the locations. The *LSF(D)* and *LSF(X)*, represent the random assignment of storage areas to any area of the plant, whereas, *LSF (D)*(aisle) and *LSF (X)*(aisle), represent the random assignment of storage to any location in the same aisle as the line location.

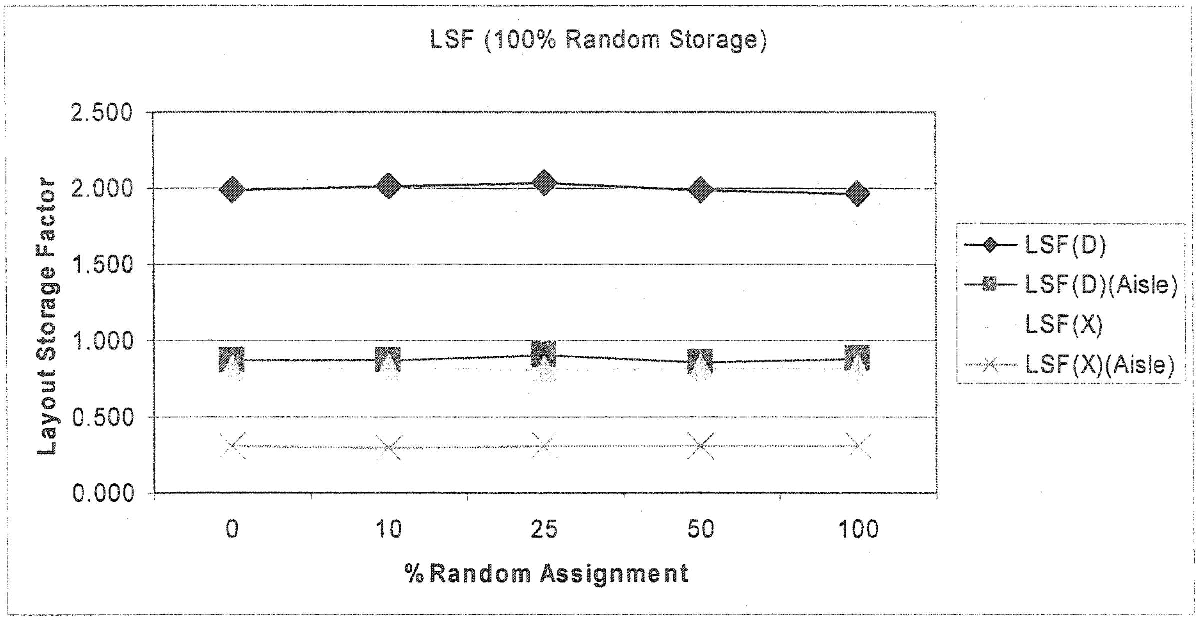


Figure 4.6.3. LSF Random Aisle and Same Aisle Comparison

It can be seen that *LSF* varies much more greatly for the direct flows than it does for the crosswise flows as a result of the lower base distances of direct flows versus crosswise flows from which the comparison is made. Obviously the introduction of randomly located off-line storage removes a great deal of the benefits of direct flows within the facility as the total travel distances become much longer (on average over twice as long for direct flows) as they were before. These smaller base differences for direct flows are also the primary reason that randomly located storage within the same aisle as the final line delivery location is deemed to have a much stronger positive impact in the results than it does for the crosswise flows.

Clearly, *LSF* is much more greatly impacted by the efficient direct flows than for crosswise flows. Unfortunately, this impact is so severe that it causes the overall *TES* value to be greater for direct flows than it is for crosswise flows even though *TW* correctly shows the larger difference for crosswise flows. This effect is caused by the much greater impact of the off-line storage inefficiency introduced to efficient direct flows than the comparable amount of inefficiency introduced to already inefficient indirect flows. Obviously *TE* would not be an acceptable substitute for *TW* in presenting the relative difference of work between direct and crosswise flow facilities, however *TE* would be a more effective metric than *TW* to use in situations where it is desired to amplify and identify inefficiency due to off-line storage in reasonably efficient direct flow facilities as *TES* would describe what *TW* may hide.

The random assignment values from 0 to 100% show some variability, however this variability does not visually appear correlated to a particular cause. Table 4.8.1 shows the comparison of the data set 6 results using 10 different random number seeds versus the data sets 6 to 10 shown in Table 4.8.2, using the same random number seed. The results indicate that the variation attributed to sets 6 to 10 is likely attributed to the randomness of the random numbers used to generate the data sets and not to any specific external cause. Evidence of this can be seen in the fact that data set 6 results in Table 4.8.1, with 10 different random number seeds varied 1% with every standard deviation and thus 95% of the results are expected to fall within +/- 2.4% of the mean. This was worse than the 0.3% of variation noted with every standard deviation on the results sets 6-10 from Table 4.8.2 using the same random number seed and in which 95% of the results can be expected to fall within +/- 1% of the mean. Runs 1 to 5 are each mean values of 10 replications using different random number seeds.

Table 4.8.1. Randomness Evaluation for LSF(X) 100% Storage, all Aisles

Crosswise	Set 6
Obs 1	0.755
Obs 2	0.773
Obs 3	0.852
Obs 4	0.798
Obs 5	0.810
Obs 6	0.801
Obs 7	0.817
Obs 8	0.788
Obs 9	0.852
Obs 10	0.792
Mean	0.8038
Std Deviation	0.0309

Table 4.8.2. Randomness Evaluation for LSF(X) 100% Storage, all Aisles

Runs 6-10	
0.8038	**Set 6**
0.8159	**Set 7**
0.8094	**Set 8**
0.8265	**Set 9**
0.8263	**Set 10**
0.8164	**Mean**
0.0101	**Std Deviation**

This evaluation was also conducted with Set 1 as shown in Table 4.9.1 in an effort to determine if there is a difference in the variation of results from crosswise flows versus that of direct flows. These results show that there is actually less variability in the data sets using different parameters as seen in Table 4.9.2, than there is in set 1 with the same parameters but with different random number seeds. Table 4.9.1 shows that the introduction of different random seeds in set 1 will cause 95% of the expected results to fall within +/- 3.5% of the mean, whereas the effects of different parameter values in data sets 1-5 shown in table 4.9.2, will cause 95% of the expected results to only fall within +/- 1% of the mean. Table 4.9.2 runs 1 to 5 are each mean values of 10 replications using different random number seeds.

Table 4.9.1. Randomness Evaluation for LSF(D) 100% Storage all Aisles

Direct	**Set 1**
Obs 1	2.118
Obs 2	1.864
Obs 3	1.981
Obs 4	2.078
Obs 5	1.994
Obs 6	2.019
Obs 7	2.121
Obs 8	2.019
Obs 9	1.812
Obs 10	1.832
Mean	1.984
Std Deviation	0.113

Table 4.9.2. Randomness Evaluation for LSF(D) 100% Storage all Aisles

Sets 1-5	
1.984	**Set 1**
2.010	**Set 2**
2.031	**Set 3**
1.989	**Set 4**
1.965	**Set 5**
1.996	**Mean**
0.025	**Std Deviation**

Intensity Parameter with Storage Factor

Introducing the *ISF* parameter to the storage factor for *TESF* produces the results as shown in Figures 4.7.1 and 4.7.2. These figures show the results for an *ISF* generated using random assignment of the storage location along the destination (line location) aisle versus the random assignment of the storage location at any location in the facility. As with the *LSF* value, the factors associated with the more efficient direct flows shown in Figure 4.7.1 are more greatly impacted by changes in *ISF* than are the less efficient crosswise flows shown in Figure 4.7.2. Otherwise, it appears that *ISF* is increasing the overall value for *TESF* according to the magnitude of the increased intensity caused within the plant due to off-line storage moves to the line as was expected.

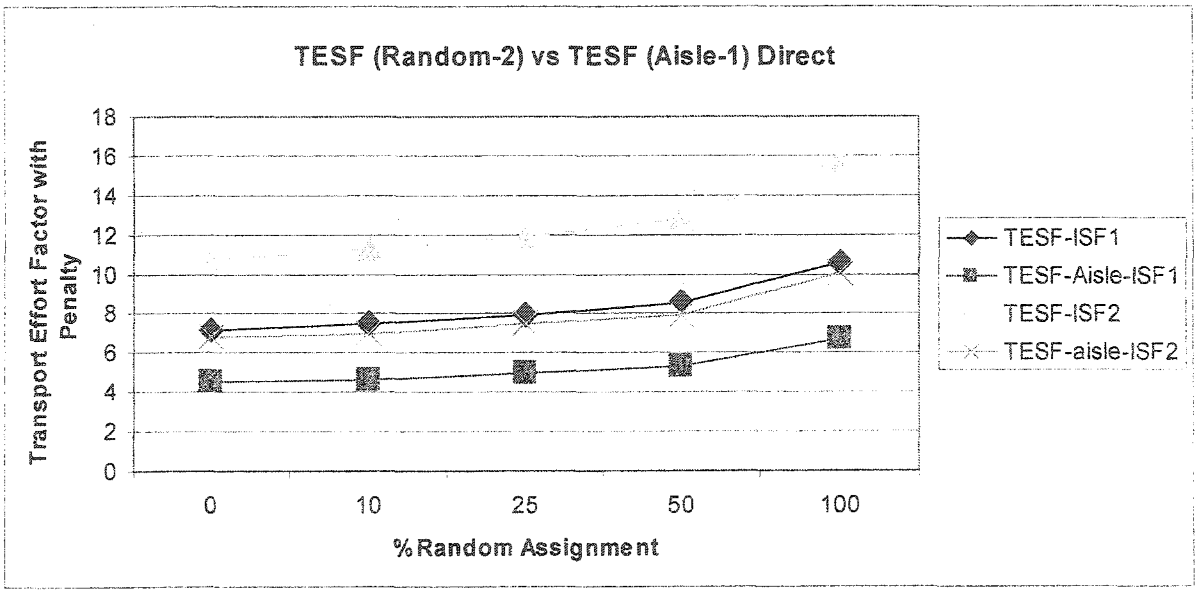


Figure 4.7.1. TESF Random Aisle and Same Aisle Comparison (direct)

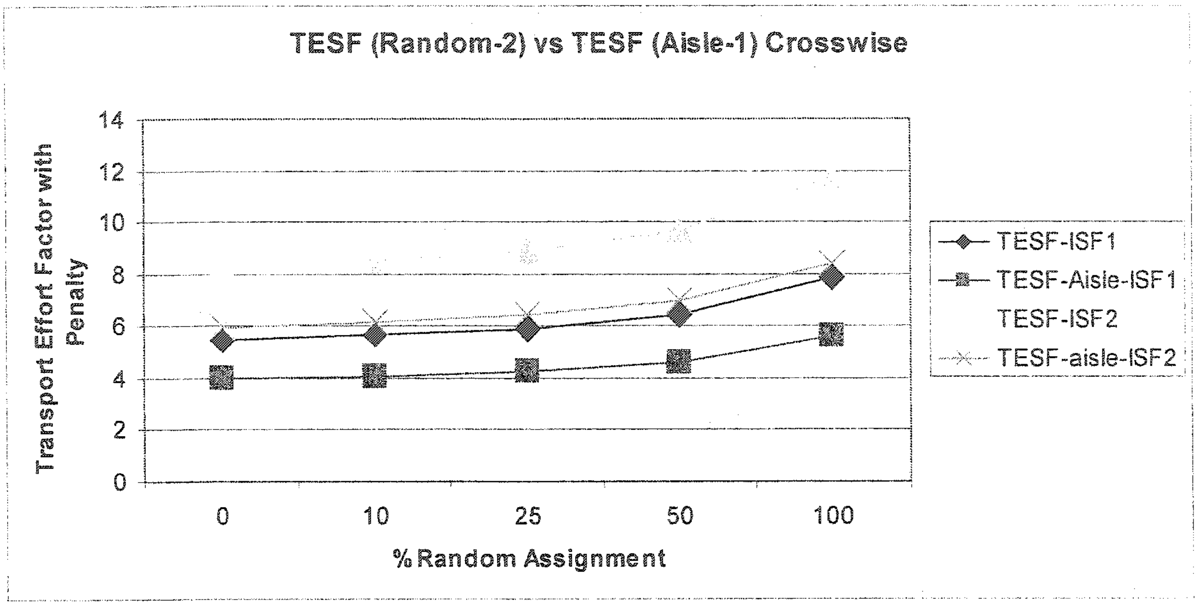


Figure 4.7.2. TESF Random Aisle and Same Aisle Comparison (crosswise)

APPLICATION OF THE METRIC

Applications in Practice

The metrics are designed for the evaluation and benchmarking of facilities that have long and contiguous work areas. These facilities are likely to have a great deal of backtracking material flow that the metric would be able to evaluate. Facilities with many horizontal and vertical aisles, arranged in a grid pattern, are likely to resemble rectilinear flow efficiencies in nearly all layout configurations, and thus would not be good candidates for the application of the metric, as the metric would likely not be sensitive enough to effectively identify inefficiencies.

The TE metric can be computed with, and without, the inclusion of off-line storage locations, as well as with, and without, the inclusion of the distance, *PD*, and volume, *V*, Scalars. The following paragraphs discuss when each method of computing TE is most applicable.

TEF – Transport Effort Factor Without Storage

The TEF factor (3.5.3) evaluates the material flow efficiency and allocation efficiency of a plant layout irrespective of average travel distance or SKU volume. This metric is useful for the evaluation of alternative layout designs such as dock additions, aisle changes and line delivery locations within a particular facility. It is also useful for the benchmarking of design efficiencies between dissimilar facilities. A notable benefit of the TEF factor over that of the TE scalar (3.5.1) is that one can also evaluate a layout design with respect to a theoretical optimum for that facility, since the PE and IA components have practical and actual upper bounds, respectively. Knowing a "best theoretical" value for a factor of a layout allows the analyst to compare the computed factor value against the theoretical optimum value and thus use this ratio to evaluate the "practical" opportunity for improvement of a given layout, or layout alternative. Therefore, while the TEF factor values between different facilities or layout alternatives could be compared directly, it is also possible to compare the ratios of these values to their theoretical ideal counterparts.

Because the TEF factor without storage does not account for travel distances, SKU volumes, as TE scalar does, it is inappropriate to use for the evaluation, or benchmarking, of indirect material handling labor requirements, as well as the evaluation, or benchmarking, of facility designs involving more than a very minimum use of off-line storage. It is important to consider that the fundamental ability of a facility to realize productive gains in material flow efficiency as off-line storage requirements are reduced, will be reflected in designs with high TEF factors that do not account for off-line storage. Therefore, the analyst may wish to evaluate the TE and TEF metrics both with and without off-line storage in an effort to evaluate the opportunity for improvement in the future.

TE - Transport Effort Scalar Without Storage

The intent of the TE scalar (3.5.1) is to introduce the facility size, and to some extent the facility shape, as well as the SKU volume into the evaluation and comparison of layout designs. Obviously, the inclusion of the average distance and volume scalars adds no value to the comparative analysis of a facility when the size, shape and SKU volume remain constant between alternatives.

Also, as discussed in the previous section, plant design efficiencies can be effectively compared using the TEF factor (3.5.3), thus the TE scalar is only required when the analyst wishes to compare the indirect material handling requirements between different facilities or facility designs. As discussed in the "Evaluation of the Metric" section, when the analyst adds in the scalars of Average distance and SKU volume, the TE scalar closely resembles actual transport effort which should correlate to indirect labor staff and equipment requirements between those facilities or alternatives. For example, an increase in the TE scalar of 30% would roughly correlate to an increase in indirect labor resources of roughly the same amount.

Finally, as mentioned with the TEF factor metric that did not include off-line storage, the TE scalar metric method would not be a valid metric for use in facilities with any significant amount of off-line storage.

The Impact of Off-Line Storage

Off-line storage locations can create a very significant inefficiency to the material flow in even the most efficiently designed facilities. This can easily be seen in Figures 4.6.1 thru 4.7.2 which clearly show that the placement of off-line storage locations anywhere outside of the direct route for material flow will often completely negate the efficiency of an efficient layout and aisle design. As a result, the analyst is strongly recommended to both design facilities with efficient material flow and then eliminate the use of off-line storage locations (especially those located off the path of the efficient material flow) with extreme vigilance.

TES - Transport Effort Scalar With Storage

As can be seen in Figures 4.6.1 and 4.6.2, the TE scalar with storage (3.9.1) will still allow the analyst to evaluate the increased inefficiency in the layout where the traditional TW metric would not. Unfortunately, these differences are minimally evident in layouts with efficiencies below that of 50% random assignment, which is likely to be the majority of designs. Therefore, while the TES metric will provide the analyst with more information than that of the TW metric (which would show nothing from perfectly efficient to totally inefficient designs) it is questionable if that improvement gained by the use of this metric would be significant.

Therefore, the use of the TES with storage may produce similar results when used in facilities whose layouts are reasonably efficient and which extensively use off-line storage located off of the efficient flow paths. In addition, analysts using current TW metrics for the evaluation of similar facilities should take notice of Figures 4.6.1 thru 4.6.3 which show that the TW-Store and TW-Aisle metrics are not capable of detecting any efficiency changes. Of course, the fact that TES differs so significantly from that of TW also indicates that using TES as a relative measure of indirect labor requirements may not be accurate, as it is hypersensitive to the use of off-line storage, and is likely to indicate excessive material handling requirements.

TESF – Transport Effort Factor With Storage

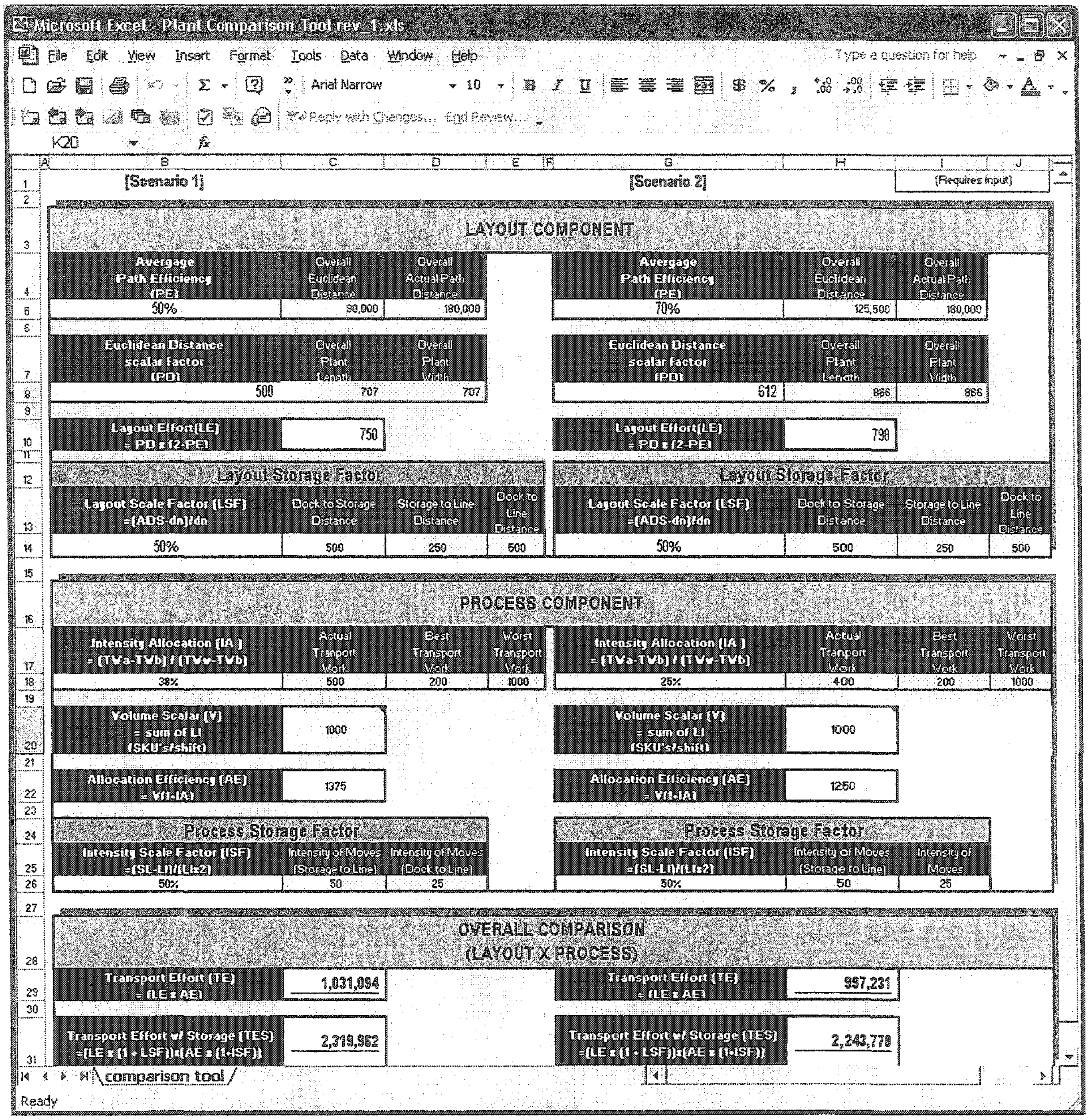
As can be seen in Figures 4.7.1 and 4.7.2, the TESF factor with storage (3.9.2) generates similar results (aside from magnitude differences) regardless if the off-line storage areas are located within the same aisle as the final line delivery location, or at any other location in the facility. In addition, the sensitivity of this metric is the same regardless of if the analysis is crosswise or direct. Finally, this metric tracks closely with the results obtained with the TES metric.

As such, it appears largely irrelevant to the analyst if the TESF method is used over that of the TES metric for the analysis of facilities using significant amounts of off-line storage. Finally, the significant inefficiency created within the layout due to the use of off-line storage causes serious difficulties in the metric's ability to effectively evaluate and benchmark facilities largely due to the highly inefficient nature of any facility employing significant amounts of off-line storage.

Example Applications in Practice

Figure 4.8 shows an example of an MS Excel spreadsheet used in industry for the computation and comparison of the proposed metrics for alternative designs of the same facility. Application software, such as FactoryFLOW, is capable of providing the input for actual and Euclidean distance information, per line location, to the MS Excel spreadsheet needed for such an analysis.

The principle use of the proposed metrics within industry has been related to the benchmarking of facility design alternatives, the evaluation of the negative impacts of off-line storage to indirect labor requirements, and finally the benchmarking of the design of multiple facilities according to each facility's TE factor.



[Scenario 1]

[Scenario 2]

(Requires input)

LAYOUT COMPONENT

	[Scenario 1]			[Scenario 2]		
	Avergage Path Efficiency (PE)	Overall Euclidean Distance	Overall Actual Path Distance	Avergage Path Efficiency (PE)	Overall Euclidean Distance	Overall Actual Path Distance
	50%	90,000	180,000	70%	125,500	180,000

Euclidean Distance scalar factor (PD)	Overall Plant Length	Overall Plant Width	Euclidean Distance scalar factor (PD)	Overall Plant Length	Overall Plant Width
500	707	707	612	866	866

	[Scenario 1]	[Scenario 2]
Layout Effort(LE) = PD x (2-PE)	750	798

Layout Storage Factor

Layout Scale Factor (LSF) =(ADS-dn)/dn	Dock to Storage Distance	Storage to Line Distance	Dock to Line Distance	Layout Scale Factor (LSF) =(ADS-dn)/dn	Dock to Storage Distance	Storage to Line Distance	Dock to Line Distance
50%	500	250	500	50%	500	250	500

PROCESS COMPONENT

Intensity Allocation (IA) = (TVa-TVb) / (TVw-TVb)	Actual Tranport Work	Best Transport Work	Worst Transport Work	Intensity Allocation (IA) = (TVa-TVb) / (TVw-TVb)	Actual Tranport Work	Best Transport Work	Worst Transport Work
38%	500	200	1000	25%	400	200	1000

	[Scenario 1]	[Scenario 2]
Volume Scalar (V) = sum of LI (SKU's/shift)	1000	1000
Allocation Efficiency (AE) = V(1-IA)	1375	1250

Process Storage Factor

Intensity Scale Factor (ISF) =(SL-LI)/(LIx2)	Intensity of Moves (Storage to Line)	Intensity of Moves (Dock to Line)	Intensity Scale Factor (ISF) =(SL-LI)/(LIx2)	Intensity of Moves (Storage to Line)	Intensity of Moves
50%	50	25	50%	50	25

OVERALL COMPARISON (LAYOUT X PROCESS)

	[Scenario 1]	[Scenario 2]
Transport Effort (TE) = (LE x AE)	1,031,094	997,231
Transport Effort w/ Storage (TES) =(LE x (1 + LSF))x(AE x (1+ISF))	2,319,962	2,243,770

Figure 4.8. Industry Spreadsheet Example of Metric Usage

CONCLUSION AND DISCUSSION

Overall Conclusions

A new metric called transport effort has been presented for the benchmarking and comparison of assembly plant designs with respect to material flow efficiency and the allocation of high intensity parts to assembly line and off-line storage locations in the facility. The metric has two main components, namely, layout efficiency, *LE,* and intensity allocation, *AE*. The *LE* consists of a scale factor representing the plant's average expected distance (1/2 of the Euclidean distance between opposing corners), and a factor value representing the efficiency of the aisle design. The *AE* also consists of a scale factor representing the volume of flow in the plant, and a factor value representing the efficiency of allocating high intensity parts to locations near docks according to the popularity rule. In addition, this work includes the development of a pair of penalty factors (*LSF* and *ISF*) to address additional inefficiencies related to off-line storage that are applied to the *LE* and *AE* components, respectively.

It was shown that *TE*, in addition to its' *LE* and *AE* components, as well as associated off-line storage penalties, is an effective and more descriptive measure of a plant's design than that of transport work *TW* in that it amplifies and isolates many of the causes of increasing *TW*. As such, *TE* now makes it possible to compare plant issues related to the layout configuration, flexible part allocation, and off-line storage policy independently.

Implications for Engineering and Industry

Automotive assembly plants are some of the largest, most complicated and most expensive industrial facilities. The general trend in mature markets with older plants is towards reducing capacity and shutting down inefficient plants. Likewise, new and more efficient facilities are being constructed in new market and labor areas globally.

Management is therefore challenged with:

- how to improve existing facilities
- how to evaluate and compare design alternatives of new facilities
- how to estimate indirect labor requirements for material handling
- and which older facilities should be shut down

Obviously these decisions involve many criteria such as; local market conditions, labor conditions, access to suppliers and the general cost structure of the facility itself. While many of these factors are relatively easy to identify and compare, the fixed and flexible issues surrounding the design of the facility have not been. This difficulty is especially evident when trying to compare assembly facilities of different sizes that make significantly different vehicles. The use of *TE* and its associated components now make these comparisons possible, systematic, and more quantitative.

Using *TE*, automotive manufacturers can achieve results comparable to the current multi-factored and indirect methods (discussed in the introduction), relatively quickly. As such, it is anticipated that deployment of *TE* would save engineering and manufacturing decision time, as well as improve the accuracy of decisions involving assembly plant material flow.

The methodology of *TE* also provides analytical value as a more effective function than that of *TW*, for use in layout improvement techniques related to automotive assembly plants. Given that the individual components of *TE* can be separated, it will become easier to evaluate layout factors in conjunction with an Aisle-based design. For example, in layout improvement techniques involving the QAP it may be more effective to use the *AE* and *LE* components as opposed to a cost function developed from *TW*. Finally, *TE* and its components are perhaps most valuable as design parameters (DP's) in Axiomatic assembly plant design (AD), as they fit much better into the evaluative and benchmarking requirements of AD that require parameter independence than does the traditional method of *TW*.

Suggestions for Further Research

While the methods are likely robust for use in commercial applications, there are several additional issues recommended for further research that could provide additional insights into the nature of plant design. For clarity, these issues have been grouped into three areas:

1. Evaluation of impacts on the model by various input parameters and distance methods.
2. Recommended extensions to the model to improve its' effectiveness by evaluating additional issues that impact efficient plant design.
3. Potential use of this metric in an optimization method.

Additional Parameters and Distance Methods

Perhaps the most significant issue for future research is that of the variance and distribution of the mean values used in the *TE* metric and its associated parameter metrics. As stated earlier, the variability and representative distribution of mean values, such as *PE*, *LSF* and *ISF* could provide additional information to the analyst that would be important for benchmarking facilities or for identifying the specific cause of facility differences and their respective corrective measures. As such, it would be beneficial to incorporate these individual variances within the *TE* metric to enhance its descriptive value.

The model utilizes Aisle-path distances exclusively, which are then compared to Euclidean distances used as a basis for determining "best case" flow. Aisle path distances are more difficult to compute than are rectilinear distances which are often used as a substitute measure for aisle distance in various layout improvement techniques. It is unknown as to the extent that aisle distances enhance the quality of *TE* versus simple Rectilinear distances.

The experiments were conducted on the model for both square facilities and long facilities with a 3 to 1 ratio of length to width. In addition, two facility sizes 1 million and 3 million square feet were evaluated. It is not known how the model responds to sizes and shapes different that those evaluated. If model response to additional sizes and shapes was significant, it could likely affect the validity of the model for comparison purposes.

Many automotive assembly plants contain blind aisles, or aisle end-caps as they are sometimes called. These blockages at the end of aisles can greatly impact material flow into and out of the included aisle. All data sets were generated with long and open aisles so the impact of end-caps on aisles has not been evaluated. While it is unlikely that the inclusion of end-caps would adversely impact the quality of *TE*, it is likely that the layout efficiency component would report worse results.

Enhancements to the Model

While travel distances are a key metric in evaluating material flow, one cannot discount the importance of unit load pick up and set down as well as material handling equipment turns in the layout. Depending upon the devices selected, the inclusion of off-line storage and additional material handling activities such as unloading and un-banding containers, a significant amount of material handling time, and effort, can exist which could impact relative indirect material handling labor requirements and effort between dissimilar facilities. In addition, the inclusion of light-boards, and staging areas, as well as the use of tow trains for material delivery can adversely impact the comparable results. Currently, none of these factors is being considered by the model.

Perhaps the greatest deficiency in the model is the exclusion of space usage. While current methods, as referenced in the introduction are quite effective, the model should include a factor for effective space usage along with the current factor for effective material flow.

Finally, additional relevant factors to be considered for a comprehensive model include the following as discussed earlier in the Introduction.

- Plant Location and Automation
- Vehicle Type and Complexity
- Vehicle Model Variance
- Depth of Construction

REFERENCES

Armour, G. C. and E. S. Buffa, "A heuristic algorithm and simulation approach to relative allocation of facilities," *Management Science*, 1963 9, 294-309.

AlmStrom P., "Systematic Design and Analysis of Manufacturing Systems – Industrial Experiences," *The Proceeding of the 14th International Conference on CAD/CAM, Robotics and Factories of the Future*, December 1-3, 1998.

Banerjee, P., Y. Zhou and B. Montreuil, "Genetically assisted optimization of cell layout and material flow path skeleton," *IIE Transactions*, 1997 29, 277-291.

Benson, B. and B. L. Foote, "Door FAST: A constructive procedure to optimally layout a facility including aisles and door locations based on aisle flow distance metric," *International Journal of Production Research*, 1997 35, 1825-1842.

Chhajed, D., B. Montreuil and T. J. Lowe, "Flow network design for manufacturing systems layout," *European Journal of Operational Research*, 1992 57, 145-161.

Chittratanawat, S. and Noble, J.S., "An integrated approach for facility layout, P/D location and material handling system design," *International Journal of Production Research*, 1999 37 (3), 683-706

Cochran D. Reynal V.A., "Axiomatic Design of Manufacturing Design," *The Lean Aircraft Initiative, Report Series*, #RP96-05-14.

Foulds L. R., Giffin, J.W., "A Graph-Theoretic Heuristic for Minimizing Total Transport Cost in Facilities Layout," *International Journal of Production Research,* (v16, n1 1978). pp27-37.

Harmonsky, C. M. and Tothero, G.K., "A multi-factor plant layout methodology," *International Journal of Production Research,* 1992 30, 1773-1789.

Houshmand Mahmoud, Jamshidnezhad Bizhan, "Redesigning of an Automotive Body Assembly Line through an Axiomatic Design Approach," http://www-mmd.eng.cam.ac.uk/mcn/pdf_files/part8_2.pdf, (date accessed: April 7, 2004).

Johnson, R. "SPACECRAFT For Multi-Floor Layout Planning," *Management Science* (v28 1982), pp407-417.

Kane, M. C. and R. Nagi, "Integrated material flow and layout in facilities design," *Proceedings of the Sixth Industrial Engineering Research Conference*, Miami FL., May 1997, 919-924.

Koopmans, T.C. and Beckman M., “Assignment Problems and the Location of Economic Activities,” Econometrics (v25, 1957), pp53-76.

LeFaive Donna, “Automotive Industry Materials Management Overview,” *AIAG Auto-Tech Conference Proceedings,* 2001.

Luxhoj, J. T., “A methodology for the location of facility ingress/egress points,” *International Journal of Operations and Production Management*, 1991 11, 6-21.

Liker Jeffrey, Lamb Thomas, *“Lean Manufacturing Principles Guide,”* Version 5.0, June 2000.

Meller, R. D. and K. Y. Gau, “The facility layout problem: recent and emerging trends and perspectives,” *Journal of Manufacturing Systems*, 1996 15, 351-366.

Francis, R. L., McGinnis Jr., L. F., White, J. A. *Facility Layout and Location: An Analytical Approach*, Englewood Cliffs, NJ: Prentice-Hall, 1992.

Montreuil, B., “A modeling Framework for Integrating layout Design and Flow Network Design,” *Proceedings of the Material Handling Research Colloquium* Hebron, KY, 1990, pp43-58.

Montreuil, B., “Integrated design of cell layout, input/output station configuration, and flow network of manufacturing systems,” American Society of Mechanical Engineers, Production Engineering Division PED 25, 1987, 315-326.

Muther, Richard, and Knut Haganas, *Systematic Handling Analysis,* Management and Industrial Research Publications, Kansas City, 1987.

Muther, R., *Systematic Layout Planning*, Management and Industrial Research Publications, Kansas City, 1966.

Noble, J.S. and Chittratanawat, S., “The integration of operational and structural issues in material flow system design,” *Material Handling Research Colloquium* (CD-ROM), June 11-14, 2000.

Ohno, Taiichi, *The Toyota Production System: Beyond Large Scale Production,* Productivity Press, 1988.

Palliyil, G. and M. Goetschalckx, “A comprehensive model for the concurrent determination of aisles and load stations for aisle-based material handling systems,” Georgia Institute of Technology, Technical Report, 1994.

Sinriech, D. and J. M. A. Tanchoco, "Design procedures and implementation of the segmented flow topology (SFT) for discrete manufacturing systems," *IIE Transactions,* 1997 29, 323-335.

Sly, David, *FactoryFLOW – A Method of Plant Layout and Material Flow Analysis in AutoCAD*, Unpublished Masters Thesis, IMSE Department, Iowa State University, 1990.

Sly, David, *FactoryPLAN – Users Manual*, Cimtechnologies Corporation, 1994.

Sly, David and Heid, Karl "Automotive Assembly Plant Benchmarking Techniques," MSUG Michigan Simulation Users Group, 1997.

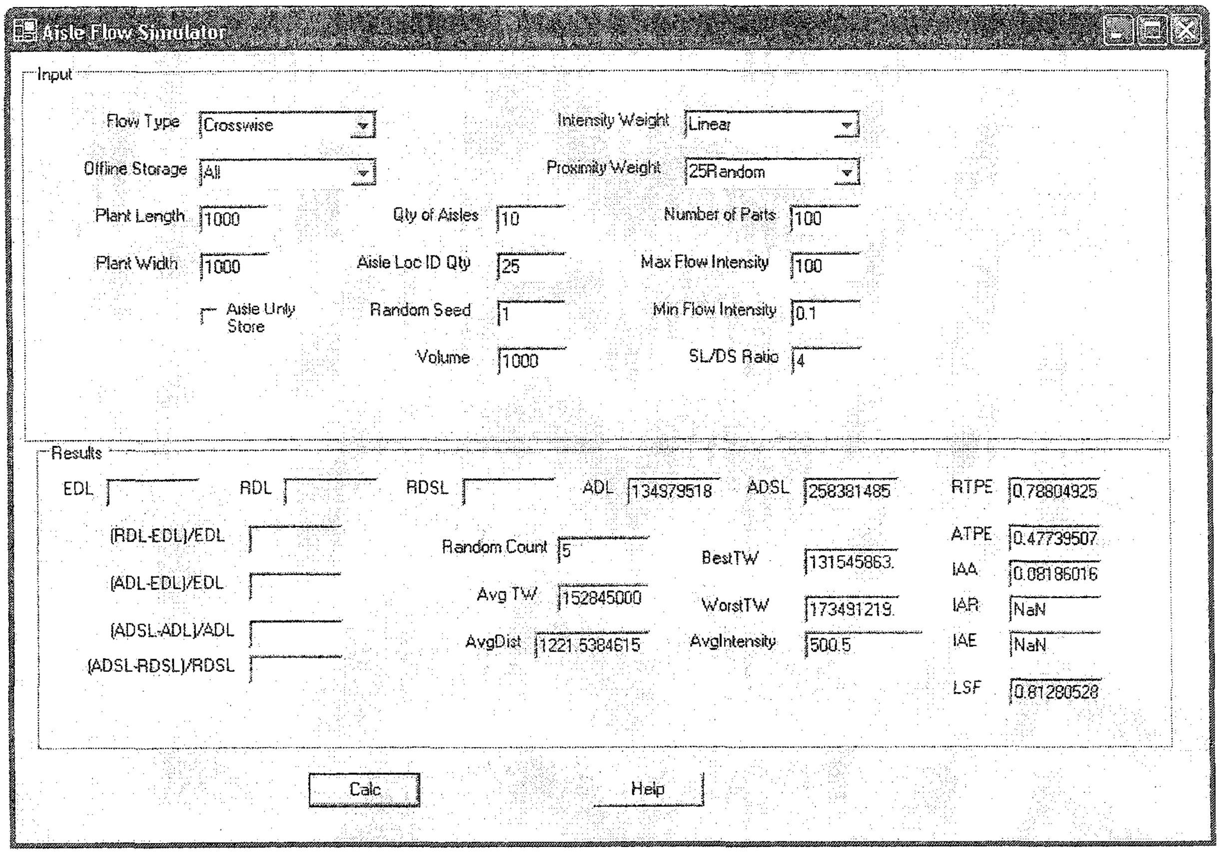
Suh N. P., 1990, *The Principles of Design*, *Oxford Press*, NY.

Tam K.Y., Li, S.G. "A Hierarchical Approach to the Facility Layout Problem," *International Journal of Production Research* (v29, 1991), pp165-184).

Tompkins, J. and White, J. *Facilities Planning,* John Wiley and Sons, New York, 1984, 352.

Urban, T.L., "A multiple criteria model for the facilities layout problem," *International Journal of Production Research*, 1987 25(12) 1805-1812.

APPENDIX A – Program Source Code



Flow Type: Crosswise
Intensity Weight: Linear
Offline Storage: All
Proximity Weight: 25Random
Plant Length: 1000
Qty of Aisles: 10
Number of Parts: 100
Plant Width: 1000
Aisle Loc ID Qty: 25
Max Flow Intensity: 100
☐ Aisle Unly Store
Random Seed: 1
Min Flow Intensity: 0.1
Volume: 1000
SL/DS Ratio: 4

ADL: 134979518
ADSL: 258381485
RTPE: 0.78804925
ATPE: 0.47739507
Random Count: 5
BestTW: 131545863.
IAA: 0.08186016
Avg TW: 152845000
WorstTW: 173491219.
IAR: NaN
AvgDist: 1221.5384615
AvgIntensity: 500.5
IAE: NaN
LSF: 0.81280528

```
    Private Sub btnCalc_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles btnCalc.Click
        'perform the calculation
        Dim flowType As String, offLine As String, intensity As String,
proximity As String, aisleEndCaps As String
        Dim aisleQty, aisleID, plantLength, plantWidth, partQty As Integer
        Dim test As Integer
        Dim endCaps As Boolean
        flowType = cboFlowType.GetItemText(cboFlowType.SelectedItem) '
Crosswise, Direct
        offLine = cboOffline.GetItemText(cboOffline.SelectedItem) '
Weighted, Random, Along Path, Along Aisle
        intensity = cboIntensity.GetItemText(cboIntensity.SelectedItem) '
Exponential, Linear
        proximity = cboProximity.GetItemText(cboProximity.SelectedItem) '
Exponential, Random
        aisleQty = Convert.ToInt16(txtAisleQty.Text)
        aisleID = Convert.ToInt16(txtAisleID.Text)
        'endCaps = chkEndCaps.Checked()
        plantLength = Convert.ToInt16(txtPlantLength.Text)
```

```
        'endCaps = chkEndCaps.Checked()
        plantLength = Convert.ToInt16(txtPlantLength.Text)
        plantWidth = Convert.ToInt16(txtPlantWidth.Text)
        partQty = Convert.ToInt16(txtPartQty.Text)
        Dim rndSeed = New
System.Random(Convert.ToInt16(txtRandomSeed.Text))
        getPaths(rndSeed, partQty, endCaps, aisleQty, aisleID,
aisleEndCaps, offLine, intensity, proximity, plantLength, plantWidth,
flowType)
        test = 1
    End Sub
    Private Sub getPaths(ByVal rndSeed, ByVal partQty, ByVal endCaps,
ByVal aisleQty, ByVal aisleID, ByVal aisleEndCaps, ByVal offLine, ByVal
intensity, ByVal proximity, ByVal plantLength, ByVal plantWidth, ByVal
flowType)
        Dim distWidth, distLength, aisleDist, minIntensity,
partIntensity(aisleQty * aisleID) As Double
        Dim width, length, maxIntensity, partIndex, routeQty, Volume As
Integer
        Dim dockX, dockY, partPosition As Double
        Dim ADL(aisleQty + 1, aisleID + 1) As Double
        Dim EDL(aisleQty + 1, aisleID + 1), RDL(aisleQty + 1, aisleID + 1),
RDSL, ADSL As Double
        Dim EDLsort(aisleQty + 1, aisleID + 1), RDLsort(aisleQty, aisleID
+ 1), ADLsort(aisleQty + 1, aisleID + 1), ADLsort2(aisleQty + 1, aisleID +
1) As Double
        Dim DGA(aisleQty + 1, aisleID + 1), DGE(aisleQty + 1, aisleID + 1),
DGR(aisleQty + 1, aisleID + 1), IG(aisleQty + 1, aisleID + 1) As Integer
        Dim partADL(aisleQty * aisleID), partEDL(aisleQty * aisleID),
partRDL(aisleQty * aisleID), partRDSL(aisleQty * aisleID),
partADSL(aisleQty * aisleID) As Double
        Dim summaryADL, summaryRDL, summaryEDL, summaryRDSL, summaryADSL
As Double
        Dim TotalEDL, TotalRDL, TotalADL, MaxRdist, MaxAdist, MaxEdist As
Double
        Dim RangeEDL, RangeRDL, RangeADL, RangeI, LSF(aisleID * aisleQty)
As Double
        Dim MinRdist As Double = 1000000.0
        Dim MinAdist As Double = 1000000.0
        Dim MinEdist As Double = 1000000.0
        Dim Intercept, Slope, StoreADLDist(aisleID * aisleQty) As Double
        Dim RandStore As Boolean
        Dim SumIAA, SumIAR, SumIAE, IAA, IAR, IAE, IntensitySort(aisleQty
* aisleID) As Double
        Dim MaxLocIntensity, MinLocIntensity, MinDist, TotIntensity,
TotalIntensity As Double
        Dim MinWidth, MinLength, ec, SW, SL As Integer
        Dim GroupRange, LocIntensity(aisleQty + 1, aisleID + 1), BestTW,
LSFSummation As Double
        Dim randCount, j, RangeCount, i, MaxError, rndCnt, GroupCounter,
lc, LSFCount As Integer
        Dim lindom, OfflineStorage As String
        Dim TempDistA(aisleQty * aisleID), TempDistE(aisleQty * aisleID),
TempDistR(aisleQty * aisleID) As Double
```

```
        Dim tempX, tempY, tempXtot, tempYtot, AdistSort(aisleQty * aisleID,
3), WorstTW, AvgDist As Double
        maxIntensity = Convert.ToInt16(txtMaxIntensity.Text)
        minIntensity = Convert.ToDouble(txtMinIntensity.Text)
        MinLocIntensity = 1000000
        distWidth = plantWidth / (aisleQty + 1)
        distLength = plantLength / (aisleID + 1)
        getWeibull()
        OfflineStorage = cboOffline.Text
        If flowType = "Crosswise" Then
            dockX = plantLength / 2.0
            dockY = 0
        Else
            dockX = 0
            dockY = plantWidth / 2.0
        End If
        For length = 1 To aisleID
            For width = 1 To aisleQty
                If flowType = "Crosswise" Then
                    If endCaps = False Then
                        aisleDist = getAisleDist(aisleID, length,
distLength)
                    Else
                        If Decimal.Remainder(width, aisleQty) > 0 Then
'odd aisle

                        End If
                    End If
                    ADL(width, length) = (plantLength / 2.0) + (width *
distWidth) + aisleDist
                Else
                    If endCaps = False Then
                        ADL(width, length) = length * distLength +
Math.Abs(width - Math.Round((aisleQty / 2.0) + 0.5)) * distWidth
                    Else
                        ADL(width, length) = length * distLength +
Math.Abs(width - Math.Round((aisleQty / 2.0) + 0.5)) * distWidth
                    End If
                End If
                EDL(width, length) = getEDL(dockX, dockY, length *
distLength, width * distWidth)
                TotalEDL += EDL(width, length)
                RDL(width, length) = getRDL(dockX, dockY, length *
distLength, width * distWidth)
                TotalRDL += RDL(width, length)
                TotalADL += ADL(width, length)
                If (ADL(width, length) > MaxAdist) Then MaxAdist =
ADL(width, length)
                If (RDL(width, length) > MaxRdist) Then MaxRdist =
RDL(width, length)
                If (EDL(width, length) > MaxEdist) Then MaxEdist =
EDL(width, length)

                If (ADL(width, length) < MinAdist) Then MinAdist =
ADL(width, length)
```

```
                If (RDL(width, length) < MinRdist) Then MinRdist =
RDL(width, length)
                If (EDL(width, length) < MinEdist) Then MinEdist =
EDL(width, length)

            Next
        Next
        txtAvgDist.Text = TotalADL / (aisleID * aisleQty)

        j = 1
        For length = 1 To aisleID
            For width = 1 To aisleQty
                TempDistA(j) = ADL(width, length)
                TempDistE(j) = EDL(width, length)
                TempDistR(j) = RDL(width, length)
                j = j + 1
            Next
        Next
        Array.Sort(TempDistA)
        Array.Sort(TempDistE)
        Array.Sort(TempDistR)
        txtRTPE.Text = TotalEDL / TotalRDL
        txtATPE.Text = TotalEDL / TotalADL
        GroupCounter = 0
        For length = 1 To aisleID
            For width = 1 To aisleQty
                For j = GroupRange - 1 To 0 Step -1
                    If ADL(width, length) >= TempDistA((j * RangeCount) +
1) And DGA(width, length) = 0 Then
                        DGA(width, length) = GroupCounter
                        GroupCounter += 1
                    End If
                    If RDL(width, length) >= TempDistR((j * RangeCount) +
1) And DGR(width, length) = 0 Then DGR(width, length) = j + 1
                    If EDL(width, length) >= TempDistE((j * RangeCount) +
1) And DGE(width, length) = 0 Then DGE(width, length) = j + 1
                Next
                ADLsort(width, length) = ADL(width, length)
                ADLsort2(width, length) = ADL(width, length)
                RDLsort(width, length) = RDL(width, length)
                EDLsort(width, length) = EDL(width, length)
            Next
        Next
        Volume = Convert.ToInt16(txtVolume.Text)
        MinDist = 1000000
        Slope = (Volume - 1) / (1 - (aisleID * aisleQty))
        Intercept = Volume - Slope
        TotIntensity = (Volume * aisleID * aisleQty) / 2
        randCount = 1
        lc = 1
        Do Until lc = (aisleID * aisleQty) + 1
            For length = 1 To aisleID
                For width = 1 To aisleQty
                    If ADLsort2(width, length) < MinDist Then
                        MinDist = ADLsort2(width, length)
```

```
                        MinWidth = width
                        MinLength = length
                    End If
                Next
            Next
            AdistSort(lc, 0) = MinWidth
            AdistSort(lc, 1) = MinLength
            AdistSort(lc, 2) = ADLsort2(MinWidth, MinLength)
            ADLsort2(MinWidth, MinLength) = 1000000
            width = MinWidth
            length = MinLength
            MinDist = 1000000
            If intensity = "Linear" Then
                IntensitySort(lc) = lc * Slope + Intercept
            Else
                IntensitySort(lc) = getWebIntensity(lc, TotIntensity,
aisleQty * aisleID)
            End If
            BestTW += IntensitySort(lc) * AdistSort(lc, 2)
            lc += 1
        Loop
        lc = 1
        ec = (aisleID * aisleQty) - 1
        Do Until lc = (aisleID * aisleQty) + 1
            WorstTW += IntensitySort(ec) * AdistSort(lc, 2)
            ec -= 1
            lc += 1
        Loop
        For partIndex = 1 To aisleQty * aisleID
            tempX = (partIndex * Slope) + Intercept
            tempY = getWebIntensity(partIndex, TotIntensity, aisleQty *
aisleID)
            tempXtot = tempX + tempXtot
            tempYtot = tempY + tempYtot
            If intensity = "Linear" Then
                partIntensity(partIndex) = partIndex * Slope + Intercept
            Else
                partIntensity(partIndex) = getWebIntensity(partIndex,
TotIntensity, aisleQty * aisleID)
            End If
            If proximity = "10Random" Then
                If randCount = 1 Then
                    lindom = "Random"
                    randCount = 2
                Else
                    lindom = "Linear"
                    If randCount = 10 Then
                        randCount = 1
                    Else
                        randCount = randCount + 1
                    End If
                End If
            ElseIf proximity = "25Random" Then
                    If randCount = 1 Then
                        lindom = "Random"
```

```
                        randCount = 2
                    Else
                    lindom = "Linear"
                    If randCount = 4 Then
                        randCount = 1
                    Else
                        randCount = randCount + 1
                    End If
                End If
            ElseIf proximity = "50Random" Then
            If randCount = 1 Then
                lindom = "Random"
                randCount = 2
            Else
                lindom = "Linear"
                randCount = 1
            End If
                End If
            If proximity = "Linear" Or lindom = "Linear" Then
                'lowest index part intensities get closest locations
                For length = 1 To aisleID
                    For width = 1 To aisleQty
                        If ADLsort(width, length) < MinDist Then
                            MinDist = ADLsort(width, length)
                            MinWidth = width
                            MinLength = length
                        End If
                    Next
                Next
                ADLsort(MinWidth, MinLength) = 1000000
                width = MinWidth
                length = MinLength
                MinDist = 1000000
            ElseIf proximity = "Random" Or lindom = "Random" Then
                rndCnt = 0
                Do
                    If rndCnt < 5 Then
                        width = rndSeed.Next(1, aisleQty)  'select random
width
                        length = rndSeed.Next(1, aisleID) 'select random
length
                    Else
                        For length = 1 To aisleID
                            For width = 1 To aisleQty
                                If ADLsort(width, length) < 1000000 Then
                                    MinWidth = width
                                    MinLength = length
                                End If
                            Next
                        Next
                        width = MinWidth
                        length = MinLength
                    End If
                    If ADLsort(width, length) < 1000000 Then
                        ADLsort(width, length) = 1000000
```

```
                        Exit Do
                    Else
                        rndCnt += 1
                        txtRndCnt.Text = rndCnt
                    End If
                Loop
            End If
            TotalIntensity += partIntensity(partIndex)
            routeQty = routeQty + partIntensity(partIndex)
            partEDL(partIndex) = EDL(width, length) *
partIntensity(partIndex)
            LocIntensity(width, length) += partIntensity(partIndex)
            If (LocIntensity(width, length) > MaxLocIntensity) Then
MaxLocIntensity = LocIntensity(width, length)
            If (LocIntensity(width, length) < MinLocIntensity) Then
MinLocIntensity = LocIntensity(width, length)
            partADL(partIndex) = ADL(width, length) *
partIntensity(partIndex)
            partRDL(partIndex) = RDL(width, length) *
partIntensity(partIndex)
            partRDSL(partIndex) = getStock("R", rndSeed, plantLength,
plantWidth, flowType, offLine, aisleID, aisleQty, width, length, distWidth,
distLength) * partIntensity(partIndex)
            If (OfflineStorage = "All") Or (OfflineStorage = "50Random"
And RandStore = False) Then
                If chkAisleOnly.Checked Then
                    SW = width
                Else
                    SW = rndSeed.Next(1, aisleQty)  'select random width
                End If
                SL = rndSeed.Next(1, aisleID) 'select random length
                StoreADLDist(partIndex) = getStockDist(SW, SL, width,
length, distWidth, distLength, aisleID, aisleQty) + ADL(SW, SL)
                partADSL(partIndex) = StoreADLDist(partIndex) *
partIntensity(partIndex)
                LSF(partIndex) = (StoreADLDist(partIndex) - ADL(width,
length)) / ADL(width, length)
                LSFSummation += LSF(partIndex)
                LSFCount += 1
                RandStore = True
            Else
                StoreADLDist(partIndex) = 0
                RandStore = False
            End If
        Next
        If (LSFCount > 0) Then
            txtLSF.Text = LSFSummation / (aisleID * aisleQty)
        Else
            txtLSF.Text = 0
        End If
        txtAvgIntensity.Text = TotalIntensity / (aisleID * aisleQty)
        txtAvgTW.Text = (TotalIntensity * TotalADL) / (aisleID * aisleQty)
        j = 1
        For length = 1 To aisleID
            For width = 1 To aisleQty
```

```
                TempDistA(j) = LocIntensity(width, length)
                j = j + 1
            Next
        Next
        Array.Sort(TempDistA)
        GroupCounter = 0
        For length = 1 To aisleID
            For width = 1 To aisleQty
                For j = GroupRange - 1 To 0 Step -1
                    If LocIntensity(width, length) >= TempDistA((j *
RangeCount) + 1) And IG(width, length) = 0 Then
                        IG(width, length) = GroupCounter
                        GroupCounter += 1
                    End If
                Next
            Next
        Next
        For length = 1 To aisleID
            For width = 1 To aisleQty
                If (IG(width, length) - DGA(width, length)) < 0 Then
SumIAA += Math.Abs(IG(width, length) - DGA(width, length))
            Next
        Next
        For i = 1 To Int(GroupRange / 2)
            MaxError += (GroupRange - (2 * i) + 1) * RangeCount
        Next
        txtIAR.Text = SumIAR / MaxError
        txtIAE.Text = SumIAE / MaxError
        For partIndex = 1 To aisleID * aisleQty
            summaryEDL = summaryEDL + partEDL(partIndex)
            summaryRDL = summaryRDL + partRDL(partIndex)
            summaryADL = summaryADL + partADL(partIndex)
            summaryADSL = summaryADSL + partADSL(partIndex)
            summaryRDSL = summaryRDSL + partRDSL(partIndex)
        Next
        txtADL.Text = Math.Round(summaryADL, 0)
        txtIAA.Text = (summaryADL - BestTW) / (WorstTW - BestTW)
        summaryEDL = summaryEDL / (aisleID * aisleQty)
        summaryRDL = summaryRDL / (aisleID * aisleQty)
        summaryADL = summaryADL / (aisleID * aisleQty)
        txtBestTW.Text = BestTW
        txtWorstTW.Text = WorstTW
        txtADSL.Text = Math.Round(summaryADSL, 0)
    End Sub
    Private Function getStockDist(ByVal FW As Integer, ByVal FL As Integer,
ByVal TW As Integer, ByVal TL As Integer, ByVal distWidth As Double, ByVal
distLength As Double, ByVal aisleID As Integer, ByVal aisleQty As Integer)
As Integer
        Dim aisleDiff As Integer, locDiff As Integer, aisleDist As Integer,
locDist As Integer
        Dim Option1 As Integer, Option2 As Integer
        aisleDiff = Math.Abs(FW - TW)
        locDiff = Math.Abs(FL - TL)
        aisleDist = aisleDiff * distWidth
        If aisleDiff = 0 Then
```

```
            locDist = locDiff * distLength
        Else
            Option1 = (FL * distLength) + (TL * distLength)
            Option2 = ((aisleID - FL) * distLength) + ((aisleID - TL) *
distLength)
            If Option1 < Option2 Then
                locDist = Option1
            Else
                locDist = Option2
            End If
        End If
        getStockDist = locDist + aisleDist
    End Function
    Private Function getStock(ByVal distMethod, ByVal rndSeed, ByVal
plantLength, ByVal plantWidth, ByVal flowType, ByVal offLine, ByVal
aisleID, ByVal aisleQty, ByVal width, ByVal length, ByVal distWidth, ByVal
distLength) As Double
        Dim storeLocLength, storeLocWidth As Integer
        Dim SLDS As Double
        SLDS = Convert.ToDouble(txtSLDS.Text)
        If offLine = "None" Then
            storeLocLength = length
            storeLocWidth = width
        ElseIf offLine = "Random" Then
            storeLocLength = rndSeed.Next(1, aisleID)
            storeLocWidth = rndSeed.Next(1, aisleQty)
        ElseIf offLine = "Weighted" Then
            storeLocLength = weightedNext(rndSeed, 1, aisleID, length)
            storeLocWidth = weightedNext(rndSeed, 1, aisleQty, width)
        ElseIf offLine = "Along Aisle" Then
            storeLocLength = rndSeed.Next(1, aisleID)
            storeLocWidth = width
        Else ' along path
            If width < aisleID - width Then
                storeLocLength = rndSeed.Next(1, width)
            Else
                storeLocLength = rndSeed.Next(width, aisleID)
            End If
            storeLocWidth = width
        End If
        getStock = getLocDist(distMethod, width, length, storeLocWidth,
storeLocLength, distWidth, distLength, aisleID) + getDockDist(distMethod,
plantLength, plantWidth, flowType, width, length, distWidth, distLength,
aisleID, aisleQty) / SLDS
    End Function
    Private Function getLocDist(ByVal distMethod, ByVal width, ByVal
length, ByVal storeWidth, ByVal storeLength, ByVal distWidth, ByVal
distLength, ByVal aisleID) As Double
        'need to evaluate endcaps
        Dim aisleDist, length1, length2 As Double
        aisleDist = Math.Abs(width - storeWidth) * distWidth
        If distMethod = "A" Then
            If aisleDist > 0 Then 'line and storage locations are on
different aisles
```

```
                If length + storeLength < (aisleID - length) + (aisleID -
storeLength) Then
                    length1 = length * distLength
                    length2 = storeLength * distLength
                Else
                    length1 = (aisleID - length) * distLength
                    length2 = (aisleID - storeLength) * distLength
                End If
                getLocDist = aisleDist + length1 + length2 + distLength
            ElseIf length - storeLength > 0 Then ' storage not at line
location
                getLocDist = Math.Abs(length - storeLength) * distLength
            Else ' Storage and line location are the same
                getLocDist = 0
            End If
        ElseIf distMethod = "R" Then
            getLocDist = (Math.Abs(width - storeWidth) * distWidth +
Math.Abs(length - storeLength) * distLength)
        Else ' Euclidean
            getLocDist = Math.Sqrt((width * distWidth - storeWidth *
distWidth) ^ 2 + (length * distLength - storeLength * distLength) ^ 2)
        End If
    End Function
    Private Function getDockDist(ByVal distMethod, ByVal plantLength,
ByVal plantWidth, ByVal flowType, ByVal width, ByVal length, ByVal
distWidth, ByVal distLength, ByVal aisleID, ByVal aisleQty) As Double
        'need to evaluate endcaps
        Dim aisleDist, length1, length2 As Double
        If flowType = "Crosswise" Then
            aisleDist = getAisleDist(aisleID, length, distLength)
            If distMethod = "A" Then
                If width = 1 Then width = 2
                getDockDist = (plantLength / 2.0) + (width * distWidth) +
aisleDist
            ElseIf distMethod = "R" Then
                getDockDist = width * distWidth + Math.Abs(length -
(plantLength / 2.0)) * distLength
            Else ' Euclidean
                getDockDist = Math.Sqrt(width * distWidth ^ 2 +
(Math.Abs(length - (plantLength / 2.0)) * distLength) ^ 2)
            End If
        Else
            If distMethod = "A" Then
                getDockDist = length * distLength + Math.Abs(width -
Math.Round((aisleQty / 2.0) + 0.5)) * distWidth
            ElseIf distMethod = "R" Then
                getDockDist = (Math.Abs(width - (plantWidth / 2.0)) *
distWidth) + length * distLength
            Else 'Euclidean
                getDockDist = Math.Sqrt(Math.Abs(width - (plantWidth /
2.0)) ^ 2 + (length * distLength) ^ 2)
            End If
        End If
    End Function
```

```
    Private Function weightedNext(ByVal rndSeed, ByVal min, ByVal max,
ByVal current) As Double
        Dim result, num, rnum As Double
        Dim range As Integer
        num = Math.Log(rndSeed.Next(1, 100) / 10.0, 2)
        rnum = rndSeed.Next(1, 100) / 100.0
        If rnum > 0.5 Then
            If (max - current) > 0 Then
                range = CInt((1 - num) * (max - current))
                result = range + current
            Else
                result = current
            End If
        Else
            If (current - min) > 0 Then
                range = CInt((1 - num) * (current - min))
                result = current - range
            Else
                result = current
            End If
        End If
        Return result
    End Function
    Private Function getExpIntensity(ByVal maxIntensity As Integer, ByVal
minIntensity As Double, ByVal partIndex As Double, ByVal partQty As
Integer) As Double
        Dim a, b, c As Double
        'getExpIntensity = partIndex * ((maxIntensity - minIntensity) /
partQty)
        'Parti Intensity = ((1 - Log10((Parti/PartQty)*9-1))*Range)+ Min
Intensity
        c = ((partIndex / (partQty * 1.0)) * 9) + 1
        a = 1 - Math.Log(c, 10)
        b = (a * (maxIntensity - minIntensity)) + minIntensity
        getExpIntensity = b
    End Function
    Private Function getWebIntensity(ByVal partIndex As Integer, ByVal
TotIntensity As Double, ByVal TotLocs As Integer) As Double
        If TotLocs = 100 Then
            Return weibull_100(partIndex) * TotIntensity
        ElseIf TotLocs = 250 Then
            Return weibull_250(partIndex) * TotIntensity
        ElseIf TotLocs = 500 Then
            Return weibull_500(partIndex) * TotIntensity
        Else
            MsgBox("WebIntensity not 100,250 or 500")
            Return 0
        End If
    End Function
    Private Function getWgtIntensity(ByVal maxIntensity As Integer, ByVal
minIntensity As Double, ByVal partIndex As Double, ByVal partQty As
Integer) As Double
        Dim a, b, c As Double
        c = Math.Round((1 - (partIndex / (partQty * 1.0))) * 10, 1)
        If (c >= 9.5) Then
```

```
            b = maxIntensity
        ElseIf (c >= 9) Then
            b = 0.5 * maxIntensity
        ElseIf (c >= 8) Then
            b = 0.2 * maxIntensity
        ElseIf (c >= 7) Then
            b = 0.15 * maxIntensity
        ElseIf (c >= 6) Then
            b = 0.1 * maxIntensity
        ElseIf (c >= 5) Then
            b = 0.08 * maxIntensity
        ElseIf (c >= 4) Then
            b = 0.07 * maxIntensity
        ElseIf (c >= 3) Then
            b = 0.05 * maxIntensity
        ElseIf (c >= 2) Then
            b = 0.03 * maxIntensity
        Else
            b = 0.01 * maxIntensity
        End If
        getWgtIntensity = b
    End Function
    Private Function getEDL(ByVal dockX, ByVal dockY, ByVal lineLocX,
ByVal lineLocY) As Double
        getEDL = Math.Sqrt((dockX - lineLocX) ^ 2 + (dockY - lineLocY) ^
2)
    End Function
    Private Function getRDL(ByVal dockX, ByVal dockY, ByVal lineLocX,
ByVal lineLocY) As Double
        getRDL = Math.Abs(dockX - lineLocX) + Math.Abs(dockY - lineLocY)
    End Function
    Private Function getAisleDist(ByVal aisleID, ByVal length, ByVal
distLength) As Double
        If length >= Math.Round((aisleID / 2.0) + 0.5) Then
            Return (aisleID - length) * distLength
        Else
            Return (length - 1) * distLength
        End If
    End Function

    Private Sub FunctionTest()
        Dim i As Double
        Dim j As Integer = 0
        Dim results(10) As Double
        For i = 0 To 10
            results(j) = Math.Exp(i)
            j = j + 1
        Next
    End Sub
    Private Sub getWeibull()
        Dim i As Integer
        Dim s As String
        FileOpen(1, "weibull.txt", OpenMode.Input)
        Input(1, s)
        For i = 1 To 100
```

```
            Input(1, weibull_100(i))
        Next
        Input(1, s)
        For i = 1 To 250
            Input(1, weibull_250(i))
        Next
        Input(1, s)
        For i = 1 To 500
            Input(1, weibull_500(i))
        Next
        FileClose(1)
    End Sub
    Private Sub txtMinIntensity_Leave(ByVal sender As System.Object, ByVal
e As System.EventArgs) Handles txtMinIntensity.Leave
        Dim value As Double
        value = Convert.ToDouble(txtMinIntensity.Text)
        If Not (value >= 0 And value <= 1) Then
            MsgBox("Value must be between 0 and 1 - inclusive",
MsgBoxStyle.OKOnly)
            txtMinIntensity.Text = "0.1"
        End If
    End Sub
```

APPENDIX B – Input Distribution

Weibull distribution for 250 locations read by program in Appendix A.

0.018864365
0.018515263
0.018169194
0.017829593
0.017496339
0.017169314
0.016848402
0.016533488
0.01622446
0.015921208
0.015623624
0.015331602
0.015045039
0.014763831
0.01448788
0.014217086
0.013951354
0.013690589
0.013434697
0.013183589
0.012937174
0.012695365
0.012458075
0.012225221
0.011996719
0.011772488
0.011552448
0.01133652
0.011124629
0.010916698
0.010712654
0.010512423
0.010315935
0.010123119
0.009933908
0.009748233
0.009566028
0.009387229
0.009211772
0.009039594
0.008870635
0.008704834
0.008542131
0.00838247
0.008225793
0.008072044
0.007921169
0.007773114
0.007627827
0.007485255
0.007345348
0.007208055
0.007073329
0.006941122
0.006811385
0.006684073
0.006559141
0.006436543
0.006316238
0.006198181
0.00608233
0.005968645
0.005857085
0.00574761
0.005640181
0.00553476
0.00543131
0.005329793
0.005230174
0.005132416
0.005036486
0.004942349
0.004849971
0.00475932
0.004670364
0.00458307
0.004497407
0.004413346
0.004330856
0.004249908
0.004170473
0.004092522
0.004016029
0.003940965
0.003867304
0.00379502
0.003724088
0.00365448
0.003586174
0.003519145
0.003453369
0.003388822
0.003325481
0.003263324
0.003202329
0.003142474
0.003083738
0.0030261
0.002969539
0.002914035
0.002859569
0.002806121
0.002753671
0.002702202
0.002651695
0.002602132
0.002553496
0.002505768
0.002458933
0.002412973
0.002367872
0.002323614
0.002280183
0.002237564
0.002195742
0.002154701
0.002114428
0.002074907
0.002036125
0.001998067
0.001960721
0.001924073
0.00188811
0.00185282
0.001818189
0.001784205
0.001750856
0.001718131
0.001686017
0.001654504
0.001623579
0.001593233
0.001563454
0.001534231
0.001505555
0.001477414
0.0014498
0.001422702
0.00139611
0.001370015
0.001344408
0.00131928
0.001294621
0.001270423
0.001246678
0.001223376
0.00120051
0.001178071
0.001156052
0.001134444
0.00111324
0.001092432
0.001072014
0.001051977
0.001032314
0.001013019
0.000994085
0.000975504
0.000957271
0.000939379
0.000921821
0.000904591
0.000887683
0.000871091
0.00085481
0.000838833
0.000823154
0.000807768
0.00079267
0.000777854
0.000763316
0.000749048
0.000735048
0.000721309
0.000707827
0.000694597
0.000681614
0.000668874
0.000656372
0.000644104
0.000632065
0.000620251
0.000608658
0.000597281
0.000586118
0.000575162
0.000564412
0.000553863
0.00054351
0.000533352
0.000523383
0.0005136

0.000504
0.00049458
0.000485336
0.000476264
0.000467363
0.000458627
0.000450055
0.000441643
0.000433388
0.000425288
0.000417339
0.000409538
0.000401883
0.000394372
0.000387001
0.000379767
0.000372669
0.000365703
0.000358868
0.00035216
0.000345578
0.000339119
0.00033278
0.00032656
0.000320457
0.000314467
0.000308589
0.000302821
0.000297161
0.000291607
0.000286157
0.000280808
0.000275559
0.000270409
0.000265355
0.000260395
0.000255528
0.000250752
0.000246065
0.000241466
0.000236953
0.000232524
0.000228178
0.000223913
0.000219728
0.000215621
0.00021159
0.000207636
0.000203755
0.000199946
0.000196209
0.000192542
0.000188943
0.000185411
0.000181946
0.000178545
0.000175208
0.000171933
Weibull-500
0.010751532
0.010637687
0.010523916
0.010411362
0.010300012
0.010189852
0.010080871
0.009973055
0.009866392
0.009760871
0.009656477
0.0095532
0.009451028
0.009349949
0.00924995
0.009151021
0.00905315
0.008956326
0.008860537
0.008765773
0.008672022
0.008579274
0.008487518
0.008396744
0.00830694
0.008218096
0.008130203
0.00804325
0.007957227
0.007872123
0.00778793
0.007704638
0.007622236
0.007540716
0.007460067
0.007380281
0.007301348
0.00722326
0.007146006
0.007069579
0.006993969
0.006919168
0.006845167
0.006771958
0.006699531
0.006627879
0.006556993
0.006486866
0.006417488
0.006348852
0.006280951
0.006213776
0.006147319
0.006081573
0.00601653
0.005952182
0.005888523
0.005825545
0.00576324
0.005701602
0.005640623
0.005580296
0.005520614
0.005461571
0.005403159
0.005345372
0.005288202
0.005231645
0.005175692
0.005120337
0.005065575
0.005011398
0.004957801
0.004904777
0.00485232
0.004800424
0.004749083
0.004698291
0.004648042
0.004598331
0.004549152
0.004500498
0.004452365
0.004404746
0.004357637
0.004311032
0.004264925
0.004219311
0.004174185
0.004129542
0.004085376
0.004041683
0.003998457
0.003955693
0.003913386
0.003871532
0.003830126
0.003789163
0.003748637
0.003708545
0.003668882
0.003629643
0.003590824
0.003552419
0.003514426
0.003476839
0.003439654
0.003402866
0.003366473
0.003330468
0.003294848
0.003259609
0.003224748
0.003190259
0.003156139
0.003122383
0.003088989
0.003055952
0.003023269
0.002990935
0.002958946
0.0029273
0.002895992
0.002865019
0.002834378
0.002804064
0.002774074
0.002744405
0.002715054
0.002686016
0.002657289
0.002628869
0.002600753
0.002572938
0.00254542
0.002518196
0.002491264
0.00246462
0.00243826
0.002412183
0.002386384
0.002360862
0.002335612
0.002310633
0.00228592
0.002261472
0.002237286
0.002213358
0.002189686
0.002166267
0.002143098
0.002120178
0.002097502
0.002075069
0.002052876
0.00203092
0.0020092

0.001987711
0.001966452
0.001945421
0.001924614
0.001904031
0.001883667
0.001863521
0.00184359
0.001823873
0.001804366
0.001785069
0.001765977
0.00174709
0.001728405
0.001709919
0.001691631
0.001673539
0.001655641
0.001637933
0.001620416
0.001603085
0.00158594
0.001568978
0.001552198
0.001535597
0.001519174
0.001502926
0.001486852
0.00147095
0.001455218
0.001439654
0.001424257
0.001409025
0.001393955
0.001379047
0.001364298
0.001349706
0.001335271
0.00132099
0.001306862
0.001292885
0.001279058
0.001265378
0.001251845
0.001238456
0.001225211
0.001212107
0.001199143
0.001186318
0.001173631
0.001161079
0.001148661
0.001136376
0.001124222
0.001112198
0.001100303
0.001088535
0.001076894
0.001065376
0.001053982
0.001042709
0.001031557
0.001020525
0.00100961
0.000998812
0.00098813
0.000977562
0.000967107
0.000956763
0.000946531
0.000936408
0.000926393
0.000916485
0.000906683
0.000896986
0.000887393
0.000877902
0.000868513
0.000859224
0.000850034
0.000840943
0.000831949
0.000823051
0.000814249
0.00080554
0.000796925
0.000788402
0.00077997
0.000771628
0.000763375
0.000755211
0.000747134
0.000739143
0.000731238
0.000723417
0.00071568
0.000708026
0.000700454
0.000692962
0.000685551
0.000678219
0.000670965
0.000663789
0.00065669
0.000649667
0.000642718
0.000635845
0.000629044
0.000622316
0.000615661
0.000609076
0.000602562
0.000596118
0.000589742
0.000583435
0.000577195
0.000571022
0.000564915
0.000558873
0.000552896
0.000546982
0.000541132
0.000535345
0.000529619
0.000523955
0.000518351
0.000512807
0.000507323
0.000501897
0.000496529
0.000491219
0.000485965
0.000480768
0.000475626
0.000470539
0.000465507
0.000460528
0.000455603
0.00045073
0.000445909
0.00044114
0.000436422
0.000431755
0.000427137
0.000422569
0.000418049
0.000413578
0.000409155
0.000404779
0.00040045
0.000396167
0.00039193
0.000387738
0.000383591
0.000379489
0.00037543
0.000371415
0.000367443
0.000363513
0.000359625
0.000355779
0.000351974
0.000348209
0.000344485
0.000340801
0.000337156
0.00033355
0.000329983
0.000326453
0.000322962
0.000319508
0.000316091
0.00031271
0.000309366
0.000306057
0.000302784
0.000299545
0.000296342
0.000293172
0.000290037
0.000286935
0.000283866
0.00028083
0.000277827
0.000274855
0.000271916
0.000269007
0.00026613
0.000263284
0.000260468
0.000257683
0.000254927
0.0002522
0.000249503
0.000246834
0.000244194
0.000241583
0.000238999
0.000236443
0.000233914
0.000231412
0.000228937
0.000226489
0.000224067
0.00022167
0.000219299
0.000216954
0.000214634
0.000212338
0.000210067
0.00020782
0.000205598
0.000203399
0.000201224
0.000199071
0.000196942

0.000194836
0.000192752
0.000190691
0.000188651
0.000186634
0.000184638
0.000182663
0.000180709
0.000178777
0.000176865
0.000174973
0.000173102
0.00017125
0.000169419
0.000167607
0.000165814
0.000164041
0.000162286
0.000160551
0.000158834
0.000157135
0.000155454
0.000153792
0.000152147
0.00015052
0.00014891
0.000147317
0.000145742
0.000144183
0.000142641
0.000141115
0.000139606
0.000138113
0.000136636
0.000135175
0.000133729
0.000132299
0.000130884
0.000129484
0.000128099
0.000126729
0.000125374
0.000124033
0.000122706
0.000121394
0.000120096
0.000118811
0.00011754
0.000116283
0.00011504
0.000113809
0.000112592
0.000111388
0.000110197
0.000109018
0.000107852
0.000106699
0.000105557
0.000104428
0.000103312
0.000102207
0.000101114
0.000100032
9.89623E-05
9.79039E-05
9.68568E-05
9.58209E-05
9.47961E-05
9.37822E-05
9.27792E-05
9.1787E-05
9.08053E-05
8.98341E-05
8.88733E-05
8.79228E-05
8.69825E-05
8.60522E-05
8.51319E-05
8.42214E-05
8.33206E-05
8.24295E-05
8.15479E-05
8.06757E-05
7.98129E-05
7.89593E-05
7.81148E-05
7.72794E-05
7.64529E-05
7.56352E-05
7.48263E-05
7.4026E-05
7.32343E-05
7.2451E-05
7.16762E-05
7.09096E-05
7.01512E-05
6.94009E-05
6.86587E-05
6.79244E-05
6.71979E-05
6.64792E-05
6.57682E-05
6.50648E-05
6.4369E-05
6.36805E-05
6.29995E-05
6.23257E-05
6.16591E-05
6.09996E-05
6.03472E-05
5.97018E-05
5.90633E-05
5.84316E-05
5.78067E-05
5.71884E-05
5.65768E-05
5.59717E-05
5.53731E-05
5.47809E-05
5.4195E-05
5.36154E-05
5.30419E-05
5.24747E-05
5.19134E-05
5.13582E-05
5.08089E-05
5.02655E-05