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Network Design Models for Discrete Material Flow Systems: A Literature Review

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The effectiveness of a material handling system depends on several factors, among them a well-thought-out flow-path design. The flow path has a significant effect on the travel time, the operating expenses, and the installation costs of the system. Moreover, the flow-path configuration has a significant impact on the complexity of the system's control software. The literature review presented in this paper describes several approaches to the design of material flow networks, including conventional type systems and more recent developments like the single-hoop, tandem configuration, SBSL, and SFT.

Keywords: AGV; Guide path design; Material handling; Network flow

1. Introduction

Although there is wide agreement on the need to integrate facility layout design and flow-path design, there are still some basic conceptual differences on how to do it. Tompkins and White [1] point to the strong relationship between the facility layout design function and the material handling design function. However, the material handling system accepted a back-stage role in most of the first facility layout design models and procedures. The relationship between these systems can be expressed by the distance measure (from pick-up point to delivery point) used in the facility layout design procedure. Although this study does not include a review of the vast litertaure on facility layout design, the following section will briefly describe the evolution of the distance measure.

1.1 The Centroid-to-Centroid Distance Measure

The first studies on facility layout design developed construction heuristics such as CORELAP [2] and ALDEP [3]. These heuristics used closeness relationships rather than flow distances, meaning no attention was given to the material handling function. A different class of heuristics was the improvement heuristics such as CRAFT [4] and its material handling evaluation extension COFAD [5]. These procedures used a rectilinear distance measure between the centroid of the origin department and the centroid of the destination department to evaluate the intermediate changes made and the final structure. The location of pick-up and delivery (P/D) stations was only a secondary consideration. However, as confirmed by Warnecke et al. [6] the centroid-to-centroid distance approximations are less representative of the actual flows compared with the P/D station flow distances.

1.2 The Pick-up and Delivery (P/D) Station Distance Measure

Recent studies in facility layout design procedures [7, 8] use a direct rectilinear distance from pick-up station to delivery station which are usually located on the department's boundaries, instead of the centroid-to-centroid assumption. However, these studies fail to relate to a specific material handling system when evaluating a change in the layout structure. In some cases, like monorails and conveyors, direct rectilinear or Euclidean distance measures are usable. In others, like AGVs and forklifts, the interdepartmental flow is possible only via the aisle network.

1.3 The Flow-Path Distance Measure

In the case of flow-path design problems the actual path distance which takes into account the physical structure of the aisle network is needed. Using this assumption the flow distance is measured from the pick-up station to the delivery station along an existing aisle network. All the studies that will be presented in this paper use this basic assumption.

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2. Issues in Designing Material Handling Systems

2.1 System Representation

Material handling systems were designed and analysed using different analytical approaches. The most common tools used are: linear and nonlinear {0–1} mixed integer programs, queueing theory models, graph theory algorithms, and simulation models. Each of these approaches needs a different system representation. For the linear/nonlinear programming models and the graph theory approach, the system is viewed as network or a non-directed graph, where pick-up stations, delivery stations, and intersections are represented as nodes and the possible flow path segments are represented as arcs. However, when queueing models are used the system is viewed as a collection of queues and servers. A similar approach is taken when describing a system in a simulation model.

Some of the issues that have to be addressed when designing and analysing material handling systems, are better served by using one system representation over the others. In order to determine flow paths, flow directions, and station location, the use of mathematical formulation or graph theory models is preferred. On the other hand, to determine input/output buffer sizes, to calculate the number of material handling devices, and to estimate the system's throughput, queueing and simulation models are preferred. There is no one dominant approach which addresses all issues in an efficient manner.

Another major issue in designing material handling systems, which is not only influenced by the physical structure of the flow paths but also by the dynamics of the system, is the carrier requirement problem. This will be described briefly in the following section. A carrier can be in different states: travelling loaded to unload, travelling empty to load, idle, either travelling or stationary, blocked owing to congestion, loading, or unloading, charging, and more. In order to determine the number of carriers a system requires, one needs to estimate all these individual states. Some are easier to estimate, like loaded trips and loading and unloading based on system requirements. However, others are quite hard to quantify owing to the randomness, like empty travel, and blocking.

2.2 Estimating the Empty Carrier Flow

Each flow assignment includes an empty trip portion. The empty trip starts from the point where the carrier receives the pick-up request. This point can be a delivery station where the carrier just completed its last assignment, a random point where the idle carrier travelling around received the call, a fixed point where the idle carrier is parked waiting for an assignment. The empty trip ends at the pick-up station that issued the request. In most of these cases it is difficult to estimate the empty carrier flow. This flow has a large impact on the network design and on the carrier requirement problem. Maxwell and Muckstadt [9] were the first to address the problem. The model presented calculates the net carrier requirement into and out of every station and dispatches empty carriers based on minimum travel distance. The model does not take into account the sequential relationships and the time dimension. Thus, this model can only offer a lower bound to the empty carrier flow. Egbelu [10] presents four methods for estimating the empty carrier flow. The first three can only serve as estimates. The fourth method is based on assigning probabilities to each flow according to need and availability and can be used for estimates under the first come first serve (FCFS) dispatching policy. Bakkalbasi [11] proves this fact and adds an additional method for calculating the empty carrier flow under the shortest travel time (STT) dispatching rule. Malmborg [12, 13] presents tightened bounds to the empty carrier flow estimates under different dispatching rules.

2.3 Estimating the Carrier Block Time

Blocking can occur owing to congestion, heavy traffic at intersections, communication delays, blocked aisles, and blocked pick-up and delivery stations. It is difficult to quantify the blocking factor owing to the large number of variables involved in the process and the large number of interactions between these variables. The most common approach to solve the problem is to use an estimated proportion of the carriers trips (loaded and unloaded) as the blocking time [10, 11].

2.4 Linear and Mixed Integer Linear Programming Models

All the formulations, regardless of specific implementation, contain two basic sets of constraints. The first set of constraints is used to ensure the connectivity of the network. Connectivity means to ensure that a flow entering a node can also leave the node. This will prevent nodes from becoming either sink or source nodes. The second set is used to ensure the reachability of the network. Reachability means that each node can be reached from any other node in the system. Gaskins et al. [14] and Ashayeri [15] point out that the use of a from–to flow chart which contains the total carrier flow in the system (loaded and empty) eliminates the need for adding reachability constraints to the model. Bakkalbasi [11] proves it by showing that the total flow, from–to chart contains enough entries such that every flow path option in the network is covered.

Objective Function Types

Different objective functions are used by these models. Some try to minimise the distance that carriers travel in the network, whether loaded travel or combined loaded and empty travel. Other models try to minimise the operation cost of such networks. The latter address the problem of whether it is cost effective to add an aisle segment to the network or not, based on two types of cost: a fixed cost related to the construction and hardware of the flow path, and a variable cost related to the travel expenses on a specific flow-path segment which is proportional to the length of the segment.

The rest of this paper will be organised as follows: this section will describe the key elements that distinguish between the different material flow structures, the other sections are each dedicated to a specific material flow structure such as the conventional, loops, tandem, SBSL, and SFT. All are classified based on some key elements such as type, number of lanes and flow direction.

2.5 Key Elements in Classifying Material Flow Networks

Physical Flow Topology (Network Type)

1. Conventional – see Fig. 1.
2. Loop – see Fig. 2.
3. Tree/spine – see Fig. 3.
4. Point.

Number of Lanes

1. Single lane: traffic is handled on one lane only.
2. Multiple lane: a distinction is made between the empty faster carriers and the loaded slower carriers. Therefore, one lane can be reserved for slow loaded carriers while the other lane is restricted to empty faster carriers, thereby improving also the system's response time.

Flow Direction

1. Unidirectional flow: the flow on each lane or set of lanes is fixed in one direction.
2. Bidirectional flow: the flow on all or some of the lanes is possible in both directions. There are several options to handle a bidirectional flow. The first is to dedicate one or more lanes for the flow in each direction. The second is to have a single lane capable of switching flow directions.

3. The Conventional Single Lane Unidirectional Flow Network

The most common type of material handling system flow path in the literature and the one which was studied the most, is the conventional single lane unidirectional flow path, like the system shown in Fig. 1. The advantage of using such a configuration is the flexibility and efficiency achieved by utilising alternative routes. On the other hand, the drawbacks are the complexity in designing the flow path, and the need for a complicated carrier supervisory controller. The design procedures presented in the following sections are using one of two basic model types. The first is based on the multi-commodity network optimisation problem, and the other is a network-based model.

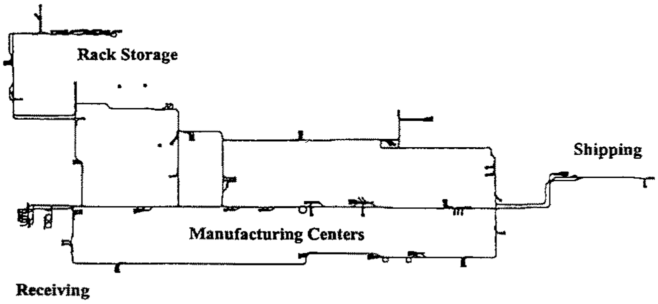
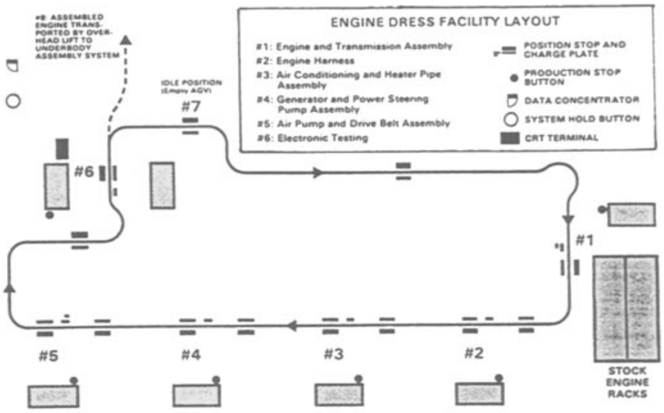
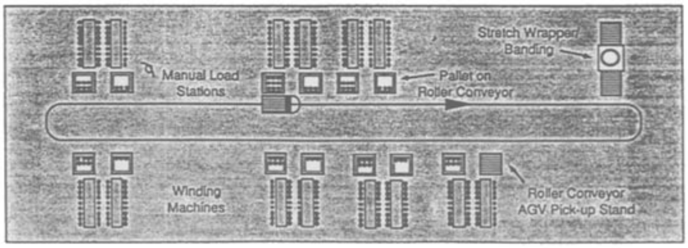


Fig. 1. Conventional flow-path configuration. [From AGVS Application Profile, vol. 3, p. 19, published by MHI.]



a: Flow Path Design by BT Systems Inc.



b: Flow Path Design by Rapistan Demag

Fig. 2. Single-loop flow-path configurations. [From AGVS Application Profile, vol. 1, p. 15 and vol. 3, p. 65, published by MHI.]

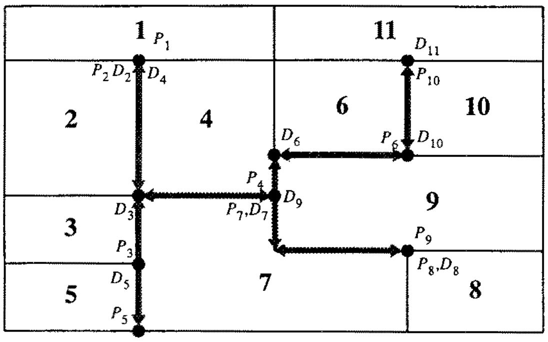


Fig. 3. Bidirectional single-lane tree flow path.

3.1 The Multi-Commodity Optimisation Model

The models presented in [11, 14, 16, 17] stem from the general multi-commodity network optimisation problem. The model deals with choices, such as the use or no use of aisle segments, the flow direction of each aisle, and flow intensity of each commodity through every segment. Each flow from pick-up to delivery is considered a commodity. The number of commodities in a network is the number of entries in the from–to flow chart. Flow conservation has to be maintained for each commodity along its route.

Bakkalbasi [11] modifies the original formulation by restricting the network to single lanes. The model is used to minimise the system's fixed construction costs and variable user cost by determining which aisle segments to add to the flow path and the flow direction of those aisles. Several heuristic procedures to solve the model are presented including network improvement procedures to refine the initial solution.

A different design approach is presented by [16]. This uses a predetermined unidirectional closed-loop flow path as the basis for the analysis, and evaluates the cost effectiveness of adding spurs around each pick-up and delivery station and shortcuts between the stations. All flow directions are prespecified. Queueing theory is used to determine the cost curves for the configurations of the different systems. These curves are then linearised and the multi-commodity optimisation program is formulated based on those linearisations. The formulation objective is to minimise the system's fixed and variable costs by determining whether to add a specific spur or a shortcut to the flow path.

Kouvelis and Lee [17] present a two-stage framework for the design of material-handling systems. The first stage includes the selection of the material-handling equipment and the second stage includes the design of the flow network. The fixed cost multi-commodity formulation is used to minimise the cost of purchasing, constructing and operating the system to meet some manufacturing goals.

3.2 The Network Based Model

The second type is the network-based model, which was developed by Gaskins and Tanchoco [18]. This model only sets the flow direction of the network segments. The constraints of the formulation define the physical characteristics of the network, and do not contain any reference to the flows in the system. The flow requirements are defined only in the objective function as a set of coefficients. By changing the objective function of the formulation, the network can be used for different jobs and job mixes.

The study [18] was an attempt to capture the system in a nonlinear {0–1} integer programming formulation model in order to determine the optimal flow-path design. The formulation developed tries to minimise the total transportation distance by setting flow directions to aisles based on a known location of pick-up and delivery stations. However, there are some drawbacks to the model. The formulation requires a very large number of constraints to represent even relatively small systems. Each flow in the system has to be identified and in every case where alternative routes between origin and destination exist, the shortest route has to be found. The model was solved using a multi-purpose optimisation package.

Usher et al. [19] suggest a modification to the original formulation. In addition to setting the aisle flow directions, this model also tries to reposition the pick-up and delivery stations. The proposed procedure contains two phases. In the first phase the system flow path is designed using the model developed in [18]. The second phase contains two steps. In the first step the pick-up stations are located by solving a one-median problem for every station. In the second step the delivery stations are located in the same way, based on the location of the pick-up stations already established in the first step. The procedure goes through several iterations of these steps until there is no change in the pick-up or delivery station location from the previous iteration. This model was further modified [20] to include the empty carrier flow as well as the loaded flow. A similar two-phase procedure to the one suggested in [19] is used. The authors point out that in the case of optimising total carrier flow, the exact placement of a pick-up or delivery station along a specific aisle is not important. Based on this, a heuristic approach of finding the "best" aisles for the pick-up and delivery stations was suggested.

Goetz and Egbelu [21] modify the original formulation so both tasks, flow direction and pick-up/delivery station location are determined simultaneously. Owing to the complexity of the problem some trade-off had to be made. Instead of considering all the flows in the system only major flows are considered, and instead of being able to locate stations at any feasible location several discrete sites have to be chosen. Even so, the formulation for relatively small systems becomes very large (the model contains variables with 9 indices).

A different version of the network-based model was developed [22]. This formulation models the decision whether to include a path segment in a network and the flow direction of the segments. The model is a well-structured linear {0–1} programming formulation, thus, simple to solve by a branch-and-bound technique. Owing to the large number of variables involved, an efficient solution procedure is needed. A material from–to flow chart in conjunction with a branch-and-bound technique make up the solution procedure. At each branch a new flow direction is set to one of the edges and the lower bound to the transportation distance is calculated. The bound considers all the edges that are not yet set as bidirectional path segments. Once a valid solution is found the upper bound is modified and branching continues until all the lower bounds calculated are larger than the smallest upper bound found.

This procedure was later modified [23]. The modified procedure makes a distinction between nodes representing pick-up and delivery stations and nodes representing intersections, and uses only the latter in the branching procedure. The reduction in the number of edges prunes the number of options that need to be considered. The order of the branching is also modified, by branching first on the most utilised edges. Therefore, the first valid solution obtained is either optimal or very close to the optimal solution.

Kim and Tanchoco [24] modified this procedure by incorporating economic considerations into the model. The objective of the model is to minimise the system's fixed construction costs and the variable user cost by determining the cost effectiveness of adding an aisle segment to the flow path, and by setting the flow directions of the aisles. A tight lower-bound calculation which enhances the branch-and-bound procedure was developed. This model can also be used to design a multi-lane bidirectional flow path, where bidirectional flows may be set if economically justified to prespecified lanes.

3.3. Other Conventional System Design Models

The following are some other flow path and P/D station design procedures which do not fall in either of the two model types described earlier.

Putrus [25] points out the importance of the flow path to the success of an assembly and manufacturing system. The study presents some guidelines and principles in the design of these flow paths.

Kiran and Tansel [26] developed a procedure to determine the best location of pick-up and delivery stations along a predefined flow path so as to minimise the system's operation cost. No fixed cost is modelled. Therefore, cost and distance are interchangeable. The model assumes that pick-up and delivery share the same location. The first conclusion made is that stations will be located next to other stations or at intersections. The second conclusion is that in the balanced case where in-flow equals out-flow, it is not important where the station is located as long as it is on the minimum cost aisle, while in the unbalanced case the station needs to be located as close as possible to the larger flow on the same aisle. This observation also holds if the location of the station is restricted to some given aisle.

A similar solution approach to [22] was developed by Venkataramanan and Wilson [27]. Their procedure uses a branch-and-bound technique to set the flow direction of the aisles, but instead of using a from–to flow chart as the flow representation, each flow in the system is identified. The aisles flow directions are set based on the shortest path from origin to destination. The bounds at each stage are calculated based on these settings. The branching is performed only if the shortest flow paths conflict in the flow direction set. The second version of the procedure also takes into account the empty carrier flow in determining the unidirectional flow. The assumption they use is that an empty carrier travels back to its origin point.

Luxhoj [28] presents a procedure, practical layout planning (PLP), to determine the location of input and output points of departments in a manufacturing system. It is composed of two computerised algorithms, a layout construction algorithm and a layout improvement algorithm. Multiple input and output points are allowed, distances are assumed to be rectilinear and follow the contour of the departments, and the specific manufacturing activities in each department are taken into account in determining the position of the points. The improvement phase is effected by the use of the pair-wise exchange method, similar to the one used by the CRAFT procedure. Although some consideration is given to the actual flow distance in the system through the use of an active flow line (AFL), the flow structure is limited to a spine flow. The entire problem is addressed in the context of facility layout design rather than flow-path design.

Kouvelis et al. [29] present a set of greedy type heuristics to design flow paths in material-handling systems. The first heuristic is based on setting the flow-path directions for each flow sequentially, where the flows are arranged in a descending order. The second heuristic uses a similar approach. However, in this case instead of using aggregate flows the flows for each individual product are used. The third heuristic sets the flow-path directions for each flow sequentially, where the flows are arranged in a flow times distance descending order. The distances are calculated based on the shortest path possible. The fourth heuristic uses the same setting criteria. However, in this cases the flow times distance values are updated based on the flow directions already assigned. The fifth heuristic assigns flow-path directions for flows which impose fewer limitations on the routing of the remaining flows. Finally, they present a simulated annealing (SA) approach to the same design problem. They conclude that although the SA produced better results a composite heuristic yields comparable results in a fraction of the time required by the SA.

A similar study [30] compares two generic approaches, the simulated annealing (SA) and the tabu search (TS), in solving a flow-path design problem. They conclude that although no superiority can be determined, the designer can expect high-quality heuristic solution from either of the two approaches.

In order to design an optimal conventional single-lane unidirectional flow path, not only the unidirectional flow has to be set but also the pick-up delivery station locations along the flow path have to be found. Owing to the fact that these two design parameters are related, both have to be simultaneously fixed. All the procedures presented in this section are suboptimal, or optimal subject to their initial assumption. The assumption is usually that the location of the pick-up and delivery stations is known and fixed, and only flow directions have to be determined. Another assumption is that the flow network is given and fixed and only P/D stations have to be located. Table 1 contains a summary of the features of each procedure.

4. The Conventional Bidirectional Flow Network

While unidirectional systems described in the previous section make up the bulk of manufacturing related studies, bidirectional systems shown in Figs. 4 and 5 have been neglected. The reason is the lack of wide-scale implementations in industry settings. Industrial use of bidirectional systems is limited, not just because of the added complexity in the system's controller, but also because of the additional and more advanced hardware needed by such systems. Although some of the studies combine the design of unidirectional and bidirectional flow networks in one model by simply comparing the set-up cost of an additional aisle segment versus the savings in the transportation cost, the difference between these models is much more fundamental. Egbelu and Tanchoco [31] point out the potential of creating efficient and cost-effective material-handling systems by using bidirectional flows. They report an improvement of 40%–100% in through-

Table 1. Design procedure characteristics for unidirectional networks.

Procedure By	Model type	Objective function	Model decisions	Solution procedure
[11]	Fixed cost multi-commodity network flow problem	Minimise cost	1. Flow direction 2. Flow intensity 3. Aisle cost effectiveness	Heuristic algorithms
[16]	Queuing theory and mixed integer linear program	Minimise cost	Aisle cost effectiveness	LINDO
[17]	Fixed cost multi-commodity network flow problem	Minimise cost	1. Equipment purchase 2. Flow path design	Framework only heuristics
[18]	Nonlinear {0–1} integer program	Minimise loaded distance	Flow direction	MPOS
[19]	Nonlinear {0–1} integer program	Minimise loaded distance	1. Flow direction 2. Station location	SAS–OR
[20]	Nonlinear {0–1} integer program	Minimise total distance	1. Flow directon 2. Station location	SAS–OR
[21]	Linear {0–1} integer program	Minimise loaded distance	1. Flow direction 2. Station location	MPSX
[22]	Linear {0–1} integer program	Minimise total distance	Flow direction	Branch and bound in FORTRAN
[23]	Linear {0–1} integer program	Minimise total flow distance	Flow direction	Branch and bound in FORTRAN
[24]	Linear {0–1} integer program	Minimise cost based on total distance	1. Flow direction 2. Aisle cost effectiveness 3. Bidirectional	Branch and bound in FORTRAN
[26]	General mathematical formulation	Minimise distance	Station location	Specific procedure developed
[27]	General mathematical formulation	Minimise total flow distance	Flow direction	Branch and bound
[28]	Facility location theory	Minimise cost	Station location	Construction and improvement models in FORTRAN
[29]	5 greedy type heuristic solution procedure and a simulated annealing approach	Minimise total flow distance	Aisle flow direction	N/A
[30]	Simulated annealing versus tabu search	Minimise total flow distance	Aisle flow direction	N/A

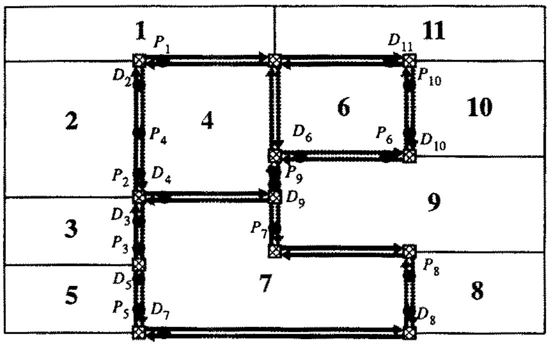


Fig. 4. Bidirectional conventional parallel (dual path) flow path system.

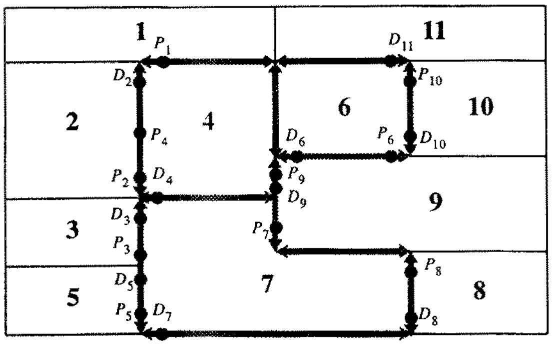


Fig. 5. Bidirectional conventional switchable (single path) flow path system.

put while operating in a bidirectional mode, depending on the type of facility layout and the number of carriers used. Vosniakos and Davies [32] compare three different flow-path configurations in an FMS shop, a unidirectional loop, a bidirectional loop, and a bidirectional spine and reach a similar conclusion.

Controlling such a bidirectional system is a complex task. Kim and Tanchoco [33, 34] present a conflict-free routeing procedure for free-path bidirectional AGV systems based on time windows, and illustrate the complexity of the problem. The studies indicate that although a free-path bidirectional system promises greater flexibility and efficiency, the controller needed to achieve that is much more complicated. On the other hand, with a small number of carriers, a bidirectional system can outperform a unidirectional system.

The decision on using a bidirectional flow path is only the first step in implementing such a system. The next decision has to be which type of bidirectional system is going to be used. Three basic conventional configurations are listed in [31]:

1. *Parallel paths.* This configuration shown in Fig. 4 is comprised of two parallel unidirectional systems. It is the easiest bidirectional system to control. However, a double set of tracks is required.
2. *Switchable paths.* In the configuration shown in Fig. 5 a single track is used for flows in both directions, i.e. a carrier entering a lane segment determines the flow direction of that lane for the entire travel duration, carriers wishing to travel in the same direction can do so and the rest wait until the lane is cleared. The configuration is complicated to control owing to flow conflicts, and may not be efficient when heavy traffic is involved.
3. *Mixed systems.* In this configuration the type of traffic on the different segments determines which combination mix to use. Dual paths are usually used for segments with heavy traffic, and the switchable paths for segments with light traffic.

Billheimer and Gray [35] develop a heuristic procedure to design a flow network which is based on an existing road and highway system. The system is modelled as a fixed-cost multi-commodity flow network. The objective of the model is to minimise the fixed and variable operation costs. Each link considered in the network permits bidirectional flows. The heuristic used starts from a complete system where all links are open and eliminates links which are not cost effective by comparing the fixed construction cost to the variable usage cost. The second phase is inserting economic links into the network, again by the same comparison. Upper and lower bounds were developed to speed up the procedure.

Egbelu and Tanchoco [31] develop guidelines for the design of single-lane bidirectional systems. The study presents an approach to resolve flow conflicts at intersections, through the use of loop buffers, siding buffers, or spur buffers. The performances of the unidirectional and bidirectional systems are compared by means of simulation. The authors conclude that the enhanced system performance can compensate for additional expenses and complexity incurred by bidirectional systems.

Gaskins et al. [14] present a design model for a multi-lane bidirectional system. The model is used to determine the number of parallel lanes required by each segment, the flow direction of each lane, and the flow intensity between nodes for each commodity, so that the transportation distance of the commodities and the number of lanes are minimised. The maximum allowable parallel lanes and the flow capacity for each lane are fixed and given. The study points to the need for an efficient heuristic solution approach.

In a similar approach, [15] presents a model for a two-lane bidirectional system. The formulation of the problem is based on the multi-commodity network flow model, and tries to minimise the cost associated with the design and operation of a carrier system. The model is used to simultaneously determine the number of carriers required by the system, the aisles that will be used, and their flow direction. The study points out that by using the empty carrier flow as one of the commodities there is no need to deal with the connectivity and reachability problems.

In the previous section an additional model was presented [24]. This model is not a bidirectional design model *per se.* However, in some cases the solution to the model can be a multi-lane bidirectional system.

Riopel and Langevin [36] present a {0–1} integer programming model to set the pick-up and delivery stations for each department among several options such that the flow times distance measure is minimised. The model assumes the facility layout including the flow path is given and fixed. The hidden assumption in the study is that bidirectional flows are allowed on the flow-path aisles. Moreover, in some cases even crossing the aisle perpendicular to the regular flows is possible. The study also presents a heuristic design procedure to solve the mathematical model. Table 2 contains a summary of all the procedure characteristics.

5. Recent Approaches to the Flow-Path Design Problem

The more sophisticated the physical network becomes, the more alternative decisions there are to explore, and the harder it is to control the system in an efficient way. There are two types of solution to the problem. The first is to address the control problem associated with conventional flow systems by applying greater intelligence to the controller function [37]. The second is to simplify the physical network by reducing the number of conflict points, thereby eliminating some of the decisions the controller has to make. This approach is very common in the transportation literature, the complexity and size are reduced and easier to handle. Another simplifying configuration is the single-loop flow path shown in Fig. 2.

5.1 The Single-Loop Flow-Path Network

There is a big difference between the conventional configuration and the single-loop configuration regarding flow direction. While unidirectional and bidirectional flows are possible alternatives in conventional systems, the single-loop is associated only with unidirectional flows, owing to the fact that the single-loop flow path contains no shortcuts and no alternative routes. Therefore, bidirectional flows will most probably cause heavy congestion and consequently grid-lock. However, in the case where the number of carriers is restricted to one per single-loop [38, 39] it is possible to use bidirectional flows. The carrier will travel clockwise or counterclockwise, whichever is shorter. Another approach is to operate two parallel flow paths as illustrated in Fig. 6. In this system carriers can use the bypass to switch directions and shorten their flow distances, achieving better response time and higher efficiency.

The single-loop configuration has been widely used in the context of fixed conveyor systems [40–42]. However, driven by advances in hardware, software and communication the single-loop system has in recent years become a viable alternative for more modern material-handling systems. Several studies have supported the single-loop concept and have developed control strategies for it.

Table 2. Design procedure characteristics for bidirectional networks.

Procedure by	Model type	Objective function	Model decisions	Number of lanes	Solution procedure
[14]	Fixed cost multi-commodity network flow problem	Minimise 1. distance 2. number of lanes	1. Flow direction 2. Flow intensity 3. Number of lanes	Predetermined number of lanes	MPOS
[15]	Fixed cost multi-commodity network flow problem	Minimise cost	1. Flow direction 2. Flow intensity 3. Aisle cost effectiveness 4. Number of carriers	Two	MIP/OMP
[24]	Linear {0–1} integer program	Minimise cost	1. Flow direction 2. Aisle cost effectiveness 3. Bidirectional	Predetermined number of lanes	Branch and bound in FORTRAN
[31]	Guidelines only	None	None	None	None
[35]	Fixed cost multi-commodity network flow problem	Minimise cost	1. Flow direction 2. Flow intensity 3. Aisle cost effectiveness	Multiple lanes	Heuristic procedure of inserting and eliminating links
[36]	Linear {0–1} integer program	Minimise flow times distance	Station location	Multiple lanes	Model solved using LINDO

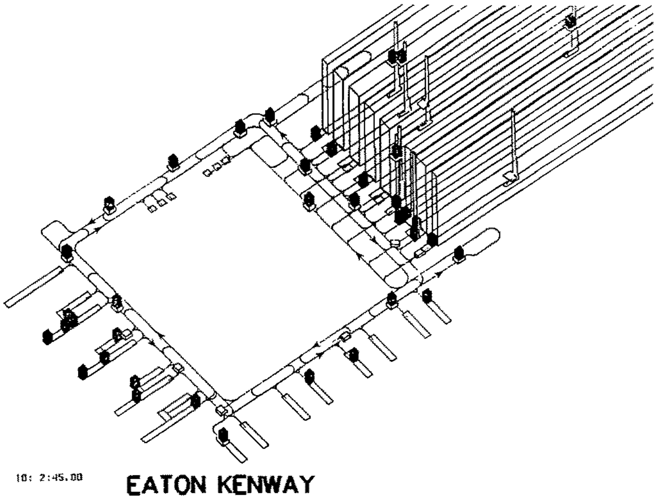


Fig. 6. Bidirectional parallel-lane single-loop flow-path configuration. [From AGVS Application Profile, vol. 1, p. 34, published by MHI].

Egbelu and Tanchoco [43] define a loop as a fixed sequence of P/D stations that vehicles visit, and denote it as the *sequential dispatching strategy*. The motivation of using such a configuration is the simplicity of the traffic control algorithms and the elimination of the shop locking possibility. Haines [44] suggests a simple control procedure for a serial loop pattern system. Bartholdi and Platzman [45] point out the efficiency of the first encounter first serve (FEFS) dispatching rule as a decentralised strategy. Bozer and Srinivasan [39] analyse the performance of a single-loop–single-vehicle system using queueing models. Egbelu [46] tackles the problem of positioning idle carriers in a single-loop system. The focus in the above studies is on the operational performance of the system, given a single-loop flow path, rather than the design of the flow path itself.

Several recent studies deal with the design of simplified flow-path networks using single loops or multiple loops. Some studies assume no aisle structure is in place and design one, as in the case of the tandem configuration. Others are limited to flexible manufacturing systems (FMS) design where only the order of machines in the loop is determined, regardless of the physical structure of the facility layout.

Afentakis [47] develops a design procedure for a loop layout for FMS. Kouvelis and Kim [48] later denote it as *unidirectional loop network layout* (ULNL). No explicit facility layout is defined and the assumption used in these studies is that predetermined sites are located along a loop, and each machine has to be assigned to one of the sites, with the objective of minimising the total distance all parts need to travel. This minimisation is achieved by minimising the number of times parts cycle the loop until completed.

Rim and Bozer [38] develop a design procedure for a similar problem. However, the unidirectional flow constraint is relaxed, and the number of carriers is limited to one. The carrier can travel clockwise or counterclockwise whichever is shorter. All stations serve as pick-up and delivery points. The objective of the model is to minimise the loaded-carrier travel distance. A branch-and-bound procedure is developed, which branches on the different machine site assignments. The lower bound at each branch is obtained by solving a shrunken generalized linear ordering problem (GLOP). A procedure to determine the degree of shrinkage needed is developed. Owing to the complexity of the problem, the problem size is limited to no more than 20 machines around the loop.

Kiran et al. [49] present a model for locating stations along a unidirectional loop using a balanced flow matrix and assuming combined P/D stations. In this case, the problem is reduced to a sequencing problem where the actual department boundaries are not used.

All these approaches are more suitable when used to design flexible manufacturing systems (FMS) where machines or workcentres need to be arranged in an efficient manner rather than to design a material flow network for a given facility layout where departments have specific geometric shapes, volume, and defined boundaries.

A different approach to the problem is presented by Tanchoco and Sinriech [50]. The OSL procedure developed for designing optimal single-loop flow paths is based on predefined facility layouts where the shape, area and boundaries of the departments are given. Efficient solution procedures for the mathematical models presented in the OSL procedure study were later developed by Sinriech and Tanchoco [51].

5.1.1 The Design Procedure for Optimal Single-Loop (OSL) Flow Paths

As explained earlier, in order to design an optimal single-loop flow-path material-handling system, both the flow path and P/D station location have to be determined simultaneously. Sinriech [52] and Tanchoco and Sinriech [50] develop an optimal single-loop (OSL) flow-path design procedure which does exactly that. The procedure is comprised of five major components.

1. The design procedure starts by identifying an initial valid loop. (By definition, a valid loop contains at least one aisle segment of each department in the facility layout). This loop is found by solving the valid single-loop problem (VSLP) using a simple construction algorithm presented in [53].
2. The second component in the OSL procedure, denoted as find all single-loops (FASL), enumerates all the loops in the facility layout, by a two-phase algorithm – an expansion phase which starts with a valid loop and finds new valid loops by expanding the initial loop. The second phase is to enumerate more valid loops by a contraction phase which starts with the last loop from the previous phase and contracts it. The algorithm goes through these two phases for several iterations until all the options are exhausted, meaning all the valid loops in the facility layout are accounted for.
3. The set that is created contains a large number of loops especially as the number of departments in the facility layout grows. Therefore, there is a need to reduce this set to a manageable size. In order to reduce the number of loops, three rules were developed. These rules eliminate loops whose performance is dominated by other loops by means of pattern comparison. Only the remaining non-dominated loops will be considered by the OSL procedure as candidates for the best loop flow path.
4. In order to determine which is the optimal loop flow path, a mixed integer programming formulation denoted as a single-loop station location problem (SLSLP) is used. The SLSLP model determines the location of the pick-up and delivery stations for each department along the single-loop flow path which minimises the total flow times distance in the system.
5. The final component in the OSL design procedure is a lower-bound calculation. Since all the loops in the non-dominated set have to be evaluated, it is more efficient to calculate a lower bound on their flow times distance than to solve each of them optimally using the SLSLP model.

5.1.2 Including Inter-Departmental Flows to the Design of Single-Loop Networks

Most flow-path design models presented in the literature overlook the impact the material flow within a department has in determining the location of pick-up and delivery stations. Two major factors need to be considered when deciding whether or not to include within-department flows in the design model:

1. The cost of moving loads within a department.
2. The size of the department.

When the relative cost of internal transportation is large compared to the transportation cost between departments, omitting this factor in the model will result in an inaccurate solution. When the size of the department is large, then the within-department transportation distances and cost may be significant. Sinriech and Tanchoco [54] develop a model which takes into account the flows within a department as well as the flows between departments in determining the location of pick-up delivery stations along a prespecified single-loop flow path. The model defines the within-department flow as the flows between pick-up and delivery stations and the department's centroid which is used as an aggregate representation of all the activity points in a department. The models also assumes that the cost ratio of the two flows is given. The model shows that by defining special points on the loop flow path called centroid projection points (CPP), a trip from an origin department to a destination department can be divided into the following segments:

1. Centroid of the origin department to the department's CPP.
2. Origin department's CPP to the pick-up station.
3. Pick-up station to delivery station along the loop flow-path network.
4. Delivery station to the destination department's CPP.
5. Destination department's CPP to the centroid of the department.

5.1.3 Advantages and Drawbacks of the OSL Flow Path Configuration

By analysing the trade-off between the conventional configuration and the single-loop configuration, a designer can choose between the two. The advantages gained by using the single-loop configuration are as follows:

1. Using the single-loop configuration offers simplicity in control and design with comparable performance to more complex systems. There are no intersections in the flow path. Thus, there are fewer chances of collision and the scheduling task becomes much more simple. There are no alternative routes in the flow path; thus, it is less complicated to make routeing decisions.
2. Using the single-loop configuration reduces the impact the empty carrier flow has on the system's performance. This attribute is analysed in [55]. The study shows the robustness of the single-loop configuration. This feature enhances the accuracy of the design, owing to the fact that some of the dynamic features and the uncertainties associated with this system are eliminated. It also reduces the importance of choosing a dispatching rule, owing to a similar performance across all rules.

The drawbacks of using a single-loop flow-path configuration are as follows:

1. The single loop is less flexible in terms of operation. In the case of failure somewhere along the loop, the entire system may be closed. None the less, the use of free-path carriers can overcome this flaw.
2. Extra transport capacity is needed owing to the fact that there are no shortcuts in the system. Once a station is passed the carrier needs to travel the entire length of the loop to get to this destination again. The use of multi-load carriers can overcome this flaw. By using multi-load carriers the extra transport capacity will be met with no additional congestion caused by more carriers in the system. Ozden [56] shows that by using this type of carrier the original number of carriers needed in the system is reduced by half. Ozden [57] also presents a controller design for a multi-load carrier system which is based on automata theory. However, further research is needed on the degree of centralisation in which the system should be operated. A more traditional controller for a multi-load carrier system is presented in [58, 59]. A major concern in a multi-load carrier system is that a load may remain on board a carrier for an indefinite amount of time. In contrast, every station in a single-loop system is visited while the carrier loops around. Therefore, each load can be delivered once its destination is reached. In the worst case, the time of delivery can be delayed by an amount equal to the load/unload time times the number of stations located between the carrier's current position and its destination.
3. The throughput of a system based on the single-loop flow path may be lower compared to a system based on a conventional flow path. This is an economic trade-off problem, gaining simplicity while loosing throughput. From the simulation runs made in [50] and [55] the loss is marginal (around 6%) and only occurs when heavy workloads are involved.

Some of these drawbacks can be alleviated through the use of bidirectional flows. Bidirectional flows possess the potential to improve the performance of material-flow networks on the other hand, as described earlier, it is not obvious how to implement bidirectional flow in a single-loop network. The solution given in Fig. 6, although possible, still requires the flows to be scheduled at the intersections to ensure collision free journeys which adds additional tasks to the control function. An alternative approach is to use the segmented bidirectional single-loop (SBSL).

5.1.4 The Segmented Bidirectional Single-Loop (SBSL)

The term segmented bidirectional single-loop (SBSL) introduced in [53] and [60] denotes a single-loop flow path which is divided into non-overlapping single carrier segments. Transfer buffers are located at both ends of each segment and serve as input/output buffers. Thus, a carrier can deposit loads which are headed to other segments and pick up loads from the other segments. The carrier has the capability to travel clockwise or counterclockwise on each segment, whichever is the shorter distance to its destination. An illustration of a SBSL flow topology with four segments is shown in Fig. 7.

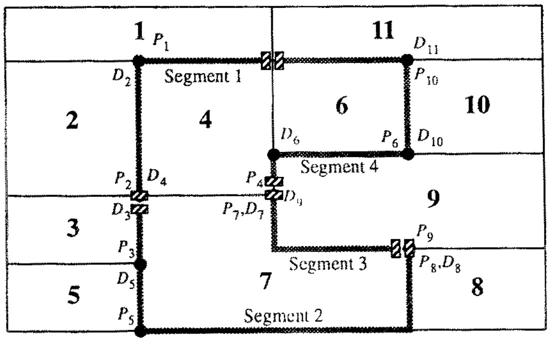


Fig. 7. The SBSL flow-path topology with four segments.

Owing to the mutually exclusive operation mode where carriers do not share common tracks, the SBSL system achieves a reduction in the time losses due to congestion, blocking, and interference. These time losses are not unique to a single-loop system. However, owing to the fact that no shortcuts exist and no alternative routes are available, these time losses are critical in a unidirectional single-loop system. On the other hand, owing to the segmentation of the flow path in the SBSL system, additional load/unload operations at the different segment transfer buffers may be required when handling a load from origin to destination. The duration of the load/unload operations is usually in the range 15–30 s. If, in a particular industrial environment, the transfer time is much longer, the use of the SBSL flow structure, especially if a large number of segment transfers are required, may be questionable.

5.2 The Tandem Configuration

As explained earlier, the performance of the single-loop configuration can be improved by simply breaking up the loop into non-overlapping smaller loops, similar to the well-known zoning approach in the transportation literature used in [61] in the dial-a-ride system. The main goal of the system is to balance the workload of all zones. As for zone transfer points, the study points out that too many points are a waste, points should be added if some delay can be eliminated.

Several studies [39, 62] were done on simplifying the conventional configuration by the use of a tandem configuration shown in Fig. 8. This approach stems from the dial-a-ride system. However, there are some differences between the

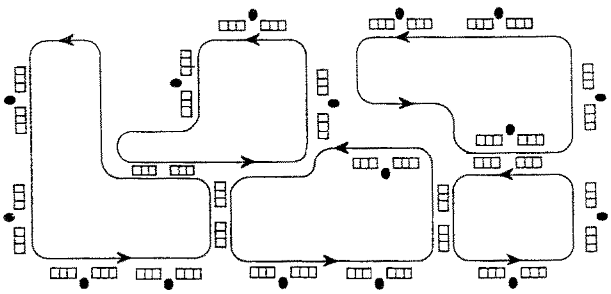


Fig. 8. Tandem flow-path configuration [38].

two. In the tandem configuration the flow path in each zone is limited to a loop. The transfer between zones is done by local input/output buffers rather than by a global transfer system. Carriers are allowed to travel in the clockwise or counterclockwise direction whichever is closer. Bozer and Srinivasan [62] present a heuristic partitioning procedure for the tandem configuration. The procedure assumes the location of machines is known, but does not take into account the shape and volume of the departments or, for that matter, the location of the facility aisles. The procedure is comprised of three phases. In the first phase, possible subsets of departments are created by solving a Euclidean TSP and choosing subsets of the defined tour. In the second phase, the feasibility of each subset is evaluated by calculating whether one carrier can meet the required workload. After eliminating the infeasible subsets, a set-covering problem is solved to determine which of the subsets will be chosen. The objective of the formulation is to balance the workload between the subsets as much as possible so that no subset will become a bottleneck. The number of loops in the final design is determined by the number of carriers needed in the system. This in turn is based on an arbitrary definition of the workload in each loop. Simulations runs [62, 63] suggest that in some cases the tandem configuration will outperform the conventional system. However, it should be noted that the physical aisle networks used in the comparison were not identical. Instead of using a single aisle network in both the tandem and conventional configurations, two different aisle structures were used.

5.2.1 Advantages and Drawbacks of the Tandem Configuration

A major advantage of the tandem configuration is that congestion, blocking and interference have been reduced, which points to a possible increase in efficiency. Additional advantages are listed in [39]. Nevertheless, some major stumbling blocks were created by the rigid restrictions of the tandem configuration.

The number of loops used in a system has a large impact on the system's performance. Let us consider a single-loop multi-carrier system. It is clear that by partitioning the single-loop flow path into two non-overlapping loops, the travel distance of some of the unit loads will be reduced, thereby reducing the time in system for those loads and improving the system's performance. On the other hand a new delay (waiting in the transfer buffers) is introduced for the loads that need to be transferred between the loops, thereby increasing their time in the system and reducing the system's throughput. The more loops the system contains the shorter the total travel distance of the loads becomes. Nevertheless, the waiting time the loads experience at the transfer buffers increases. As long as the reduction in travel distance (time) is larger than the increase in waiting time, an additional loop will improve the system's overall performance. Once the delay time becomes larger, the system's performance will deteriorate with any additional loop added to the system. This means there is an optimal partitioning for every system. Therefore, the objective of every partitioning procedure should be not just to balance the workload in each loop, but also to choose loops that minimise the number of unit loads transfers between them. Bozer and Park [64] present a new partitioning scheme for the tandem configuration. In this procedure they combine internal flows in the zone and external flow between zones. They also try to steer away from the original tandem configuration definition of "non-overlapping, single-vehicle closed loops with additional P/D points provided as an interface between adjacent loops" [62] and alleviate the closed loop constraint on the flow structure within each zone. However, no mechanism for determining the new flow structures within the zones is given.

1. Restricting the number of carriers to one per loop, poses some problems. The carriers will most probably become the bottleneck of the system. Therefore, a manageable workload has to be created. This can be achieved by restricting the machines around the loop to a small number. This causes the need for a large number of loops, and consequently a large number of carriers will be needed in the system. This in turn may not be cost effective. The system also becomes more sensitive to the carriers' reliability.
2. The size of a zone is limited by the workload capacity of one carrier. Hence, this restriction forces the way the system is going to be partitioned. Therefore, it is very likely that the best system partitioning, as explained earlier, will not be used and as a result additional zone transfer will be needed by the system.
3. The partition also determines the sensitivity of the tandem configuration to carrier failure. Once a carrier fails an entire part of the manufacturing system is shut down and production is interrupted.
4. As explained earlier, the need for routeing carriers in the tandem configuration has been eliminated. None the less, in most cases a load needs to be handled by more than one carrier on its route from origin to destination. Therefore, routing decisions still need to be made for the loads. Lin et al. [65] define it as the load routing problem (LRP) and solve the static case through the use of a mathematical model.

Table 3 presents a summary of each of the procedures presented in this section.

6. The Spine and Tree Flow Network

The spine flow network and tree flow networks like the one shown in Fig. 3, are common configurations for several material-handling systems like cranes, monorails, and conveyors in conjunction with assembly and flow-line manufacturing systems. This is due to its simple and efficient structure. However, it is much more difficult to operate a multi-carrier-based material-handling system using this configuration because of the lack of flexibility in the configuration which prohibits the carriers to exploit their capabilities.

Similarly to the single-loop, no shortcuts or alternative routes exist in this type of system. Therefore, using bidirectional flows will most probably cause heavy congestion and possibly gridlock. Thus, the number of carriers per spine has to be limited to only a few carriers, similarly to the bidirectional

Table 3. Designprocedure characteristics for single-loop networks.

Procedure by	Procedure name	Initial assumptions	Flow type	Number of vehicles	Number of loops	Model type	Objective function	Model decision	Solution procedure
[38]	Bidirectional circular loop problem (Bi-CLP)	1. Loop defined 2. Discrete sites given	Bidirectional	Single vehicle	Single loop	General mathematical formulation	Minimise distance based on flow between departments	Assign M/C to sites	Branch and bound in FORTRAN
[47]		Equally spaced discrete sites	Unidirectional	Not specified	Single loop	Graph theory, {0–1} mixed integer program	Minimise distance based on flow between departments	Assign M/C to sites	Interchange heuristic
[50]	Optimal single loop (OSL)	1. Size and shape of dep. defined 2. Aisle location given	Unidirectional	Multi vehicles	Single loop	5-stage procedure including two {0–1} integer program	Minimise distance based on flow between departments	1. Guide path design 2. Station location	Enumeration and elimination in FORTRAN
[54]	Optimal single loop (OSL)	1. Size and shape of department defined 2. Aisle location given 3. Single loop defined	Unidirectional	Multi vehicle	Single loop	{0–1} mixed integer program	Minimise cost based on flow within and between departments	Station location	Modified CPLEX
[61]	Dial-a-ride	Road and high network exists	Unidirectional	Multi vehicles	Multi-routes but no loop *per se*	Only guide lines presented	Improve response time	Vehicle sequence and tour	Not given
[62]	Tandem configuration	Location of M/C given	Bidirectional	Single vehicle per route	Multi loop	3-stage procedure including TSP and set covering	Balance work-load between loops	Define the loop subsets	Specific designed procedure including LINDO

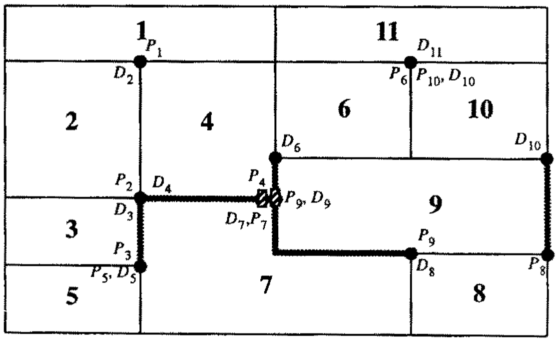


Fig. 9. Segmented flow topology (SFT) type network.

single-loop network. In order to alleviate this problem segmented flow topology (SFT) has been developed [60, 66]. In the study a distinction is made between fully connected networks such as the conventional and single-loop type systems, partitioned systems such as the tandem configuration, and split type networks such as the SFT. This type of system combines all possible flow structures described earlier: conventional, loop, spine and tree.

6.1 The Segmented Flow Topology (SFT)

In manufacturing systems, flow requirements exist only between a few points as defined by a given process plan or a from–to flow matrix. Therefore, in material handling related networks a disjoint physical flow solution can be a valid one as long as it supports the logical material flow requirement, i.e. that the flow graph representing the from–to flow matrix can be a disjoint graph and the physical flow paths used to support the logical flows can be mutually exclusive. In contrast to the partitioned system which still retains a physical connection between the different parts, the split system consists of mutually exclusive zones which do not interact. In this type of system not every node can be reached from any other node. This holds only when considering nodes across different zones. However, only one material-handling device handles a load from origin to destination. An SFT system which is comprised of two single node zones, a tree zone, and a spine zone is illustrated in Fig. 9.

The segmented flow topology (SFT) is comprised of one or more zones, each of which is separated into non-overlapping segments with each segment serviced by a single material-handling device. Transfer buffers are located at both ends of each segment (similar to the SBSL type network) and they serve as the interface between the segments. These buffers serve as input/output buffers where a material handling device can deposit loads which are headed to other segments and pick-up loads from other segments. In order to eliminate blocking, the buffers have to be able to serve both sides of the segments simultaneously. The material handling device has the capability to travel forward or backward on each segment whichever direction is a shorter distance to its destination.

Using the SFT means the shortest path from any pick-up station to any delivery station can be traversed. All segments are bidirectional and mutually exclusive which in turn contributes to a more efficient system since no congestion, blocking and interference are present. Table 4 presents a comparison of the different features between the SFT, tandem, single-loop and conventional systems.

The SFT design procedure is comprised of the following 5 steps.

1. All the shortest path alternatives for each flow in the system between nodes of the origin departments to nodes of the destination departments are determined.
2. The P/D station location that will minimise the cost of the system is determined, based on a trade-off between the cost of setting up an additional pick-up and/or delivery station compared with the gain in the transportation cost.
3. The flow-path network is identified through the use of the pick-up and delivery station locations and the shortest path algorithm.
4. Segmentation of the designed flow path based on the number of material-handling devices required in each zone.
5. Based on all the information the final step is the system's total cost calculation.

7. Summary

It is clear that there is an incentive to develop simple flow structures to manage and control, such as the single-loop and tandem configurations. However, as pointed out through this review, these flow structures still lack flexibility and efficiency.

Table 4. Comparison of the different system features.

System features	SFT	Conventional	Single-loop	Tandem
Number of mutually exclusive zones	One or more zones which are further segmented into non-overlapping segments	One zone only: these are fully connected system	One zone only: these are fully connected system	Split system which retains connectivity trough transfer buffers
Number of carriers per zone	Multiple	Multiple	Multiple	Single
The ease of operating a with bidirectional system	Part of the system definition	Difficult	Very difficult	Very simple
Split P/D stations	Part of the system definition	Not available	Not available	Not available
Minimum cost design objective	Part of the system design procedure	Available	Available	Available

Therefore, there is still a need to develop other simple flow topologies which possess a higher degree of efficiency in operation without compromising the simplicity in control similar to the SBSL and SFT structures.

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