MATERIAL TRANSPORT SYSTEM DESIGN IN MANUFACTURING

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To my father and my wife

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LIST OF SYMBOLS

T	Set of tasks with indices s, t, and w
$T(e)$	Set of tasks that are compatible with technology e
K	Set of task-resource combinations with index k
$T(k)$	Set of tasks of task-resource combination k
e_k	Technology of task-resource combination k
E	Set of technologies with index e
$N(e)$	Set of nodes of technology e with indices i and j
$A(e)$	Set of arcs of technology e with index (i, j)
$o(t)$	Origin of task t
$d(t)$	Destination of task t
P	{Constraints (4-5) and $\overline{f}_{ijtke} \geq 0$, $\underline{f}_{ijtwke} \geq 0$, $0 \leq y_{ije} \leq 1$}
$\mathbf{P_a}$	{Constraints (4-5a) and $\overline{f}_{ijtke} \geq 0$, $\underline{f}_{ijtwke} \geq 0$, $0 \leq y_{ije} \leq 1$}
Y	Network topology constraints associated with a specific technology class
A	A $\|T\| \times \|K\|$ task-combination matrix for system selection
a_{tk}	Element of task-combination matrix **A** with value 1 if task t is included in combination k and 0 otherwise
C^{v}_{ije}	Network operating cost of technology e on arc (i, j)
C^{f}_{ije}	Network construction cost of technology e on arc (i, j)
C_k	Network construction and operating cost of task-resource combination k
C^{C1}_{e}	Fixed cost of control system of employing technology e

C_e^{C2}	Incremental cost of control system of employing technology *e*, based on the number of tasks in a cluster
CC_k	The capital investment of a tasks-resource combination *k*
U_{ije}	Capacity of technology *e* on arc (*i*, *j*)
L_{ij}	The width capacity on flow path segment (*i*, *j*)
h_{ijk}	The required space for combination *k* on arc (*i*, *j*)
F_{te}	Demand of task *t* on technology *e*, in unit loads
D_e	The sum of flows of the tasks that can be handled by technology *e*
x_{tke}	1, if task *t* is assigned to cluster *k* and served by technology *e*; 0, otherwise.
y_{ije}	1, if arc (*i*, *j*) is used by technology *e*; 0, otherwise.
$\overline{f}_{ijtke}$	Loaded travel flow of task *t*, cluster *k*, technology *e* on arc (*i*, *j*).
$\underline{f}_{ijtwke}$	Empty travel flow between task *t* and *w*, cluster *k*, technology *e* on arc (*i*, *j*)
g_{itwke}	Ratio of Kuhn's empty travel representation at node *i* between task *t* and *w*, cluster *k*, technology *e* with lower bound L_g and upper bound U_g
$\underline{g}_{itwke}$	Numerator of g_{itwke} with lower bound $L_{\overline{g}}$ and upper bound $U_{\overline{g}}$
$\overline{g}_{itwke}$	Denominator of g_{itwke} with lower bound $L_{\underline{g}}$ and upper bound $U_{\underline{g}}$
$\hat{g}_{twke}$	Quadratic terms $x_{tke}x_{wke}$ in the numerator of the empty flow ratio
$\Phi(i, j)$	The number of vehicles required for arc (i, j) per time period

LIST OF ABBREVIATIONS

MTS	Material Transport System
MTSDP	Material Transport System Design Problem
O-D	Origin-Destination
I/O	Input/Output
MINLP	Mixed Integer Nonlinear Programming
MILP	Mixed Integer Linear Programming
AGV	Automated Guided Vehicle
LP	Linear Programming
FNDP	Flow Network Design Problem
CSP	Clustering/Set Partition
CF	Compact Formulation
V	Vehicle technology
VM	Manual-driven Vehicle
VA	Automated Vehicle
C	Floor-support Conveyor
O	Overhead technology
OT	Overhead Trolley Conveyor
OP	Overhead Power-and-free Conveyor
B	Bridge crane

SUMMARY

This dissertation focuses on the material transport system design problem (MTSDP), integrating decisions of technology selection and flow network design. This research is motivated by the design of material transport systems (MTS) in manufacturing plants. The objective is to design a MTS with minimum lifetime costs, subject to service requirements, flow network restrictions, and limited resources. We characterize the MTSDP from the perspectives of task requirements, transport technology, and space utilization. A classification is proposed for transport technologies such that instances in the same class share the same properties, and a decision framework is proposed to emphasize the inter-relationships of three major decisions: task clustering, network connecting, and technology selection. We consider fixed and variable costs, arc capacities, and empty travel in our formulations.

We propose two solution approaches for the MTSDP. The first is the compact formulation (CF) approach where the three major decisions are handled by a mixed integer non-linear programming (MINLP) formulation. Relaxation techniques are applied to linearize the model. The solution of the resulting linear formulation (MILP) provides a lower bound to that of MINLP. A tightened formulation reduces the computational time by a factor of 3.85. The experiment also shows that when control system costs are significant, designs with multiple-task clusters are more economical than those restricted to single-task clusters.

The other approach is clustering/set partition (CSP), where the three decisions are decomposed and solved sequentially. In an example MTS design problem, three methods

are compared: CSP, a GREEDY approach from the literature, and enumeration. CSP finds the optimal solution, while GREEDY results in 31% greater costs. A similar comparison with another example is made for the CF and CSP approaches.

We apply the CSP approach in a case problem, using data from an auto parts manufacturer. We include flow path crossing constraints and perform experiments to determine solution quality over a range of small problem sizes. The largest difference from optimality is 3.34%, and the average is 0.98%. More importantly, based on these experiments, it seems there is no evidence that the difference percentage grows with an increase in the number of tasks.

CHAPTER 1

INTRODUCTION

1.1 Material Transport System

This research addresses the problem of material transport system (MTS) design for general manufacturing facilities. The word *material* refers to a set of discrete parts. A discrete part can be a work-in-process or finished good. *Transport technology* refers to technologies that are used to move material from one location to another location within a manufacturing facility. The typical examples of transport technology in a manufacturing facility are industrial vehicles, conveyors, and cranes. *Material transport system* can be seen as a set of transport technologies serving transport requests within a manufacturing facility. The word *task* refers to a measure of steady-state material flow by unit load. It is defined by origin, destination and other material attributes.

In this research, we use three terminologies to describe the space requirements of task and technology. *Layout graph* is a graphical description of where all technologies can be located and operated. *Working network* is derived from layout graph. It is defined by a technology or technology class and all feasible tasks of that technology. *Flow network* is defined by a technology subsystem and the selected tasks. The nodes and arcs of a flow network are subsets of those in the corresponding working network.

This research is motivated by the design of material transport systems in manufacturing plants. Because of the flexibility of technologies, there is often more than one technical solution for each transport request. In addition, material transport technologies exhibit considerable fixed cost. As a result, it is often better to select fewer transport technologies and assign several transport requests to one technology to achieve economy of scale.

1.2 Issues Related to MTS Design

MTS design in a manufacturing facility is an extremely complex job. The MTS design is part of facility planning and it relates to other planning decisions. Moreover, the decisions made in the MTS design affect the operational planning of transport functions. The interactions between decisions within the planning of MTS also complicate the MTS design processes.

1.2.1 Inter-dependencies in the Design Decisions of MTS

A classical facility layout process is illustrated in Figure 1-1. Blocks represent a space partition of the facility. Let us denote each block as a workstation. A workstation is formed by a set of machines and their required space. One way to generate blocks is through the analysis of space requirements based on manufacturing and engineering data, as described in Francis, McGinnis et al. (1992). The material flow is a measurement of flow intensity between workstations. The relative locations of blocks could be decided by the intensity of material flow between blocks. This would result in the block layout, a scaled graphical representation of the facility. Note that the input and output points of a workstation can be decided by the intra-workstation layout and/or the material flow intensity. The block layout here contains the input and output points of a workstation. Combining the block layoutwith technology flow, a measure of material flow by technology units, gives the detailed layout design of the facility. The dashed arrows indicate the possible feedback to each step of design process.

1.2.2 Intra-dependencies in the Design Decisions of MTS

Within the domain of MTS planning, decisions need to be made ranging from long-term investments to daily operations. In Figure 1-2, these decisions are listed based on a green field design. For the applications of re-design, some of the decisions might be specified in advance.

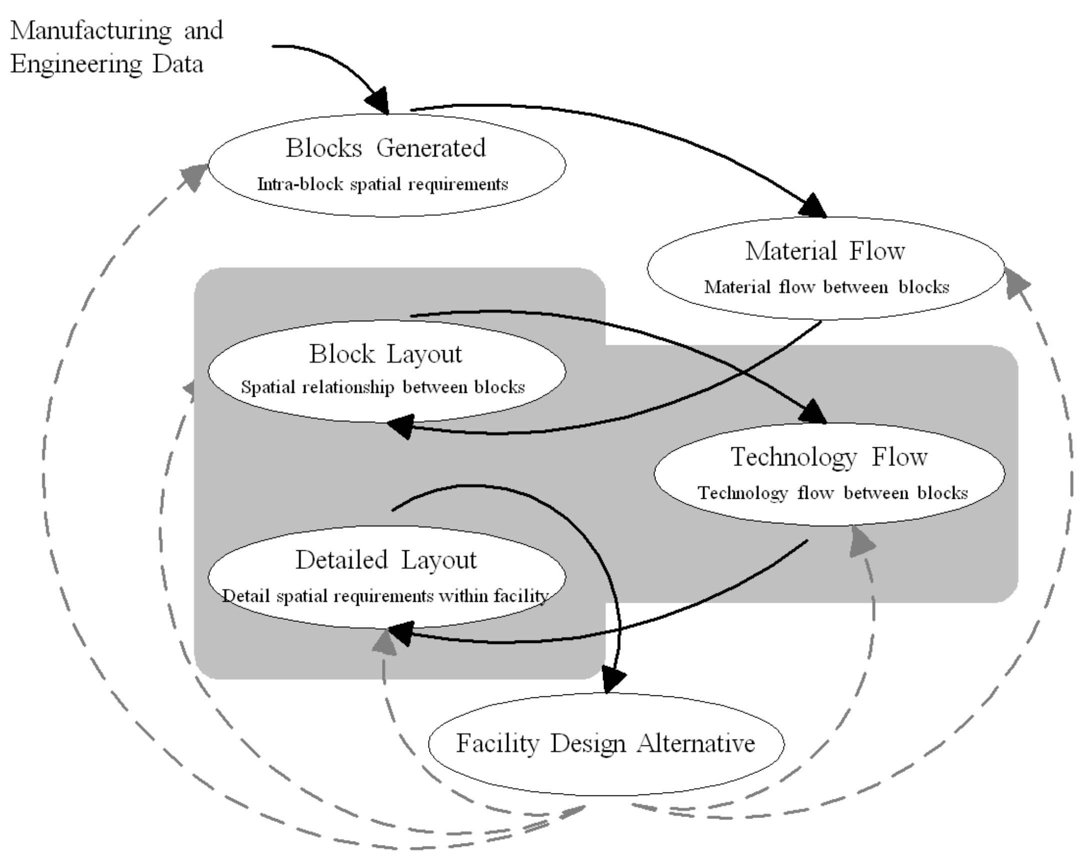

Figure 1-1: Inter-dependencies in MTS Design and Facility Layout

The third decision in the planning of MTS is the operation of each flow network, which consists of routing and control decisions. The operation planning can be changed from one production batch to another. The operation planning involves some short-term planning issues like dispatching. From the perspective of decision time span, the network operation is a mid/short term decision.

The selection and sizing of transport technology depend on the intensity of the transport operation and, therefore, the flow network design. The flow network design also depends on the behavior of the selected technology. Moreover, the flow network design restricts the variety of specific operations. The routing/dispatching policies also contribute to the complexities of flow network design, technology sizing and, therefore, technology selection. Therefore, the design decisions of MTS planning range from long-term strategic planning to daily operational control.

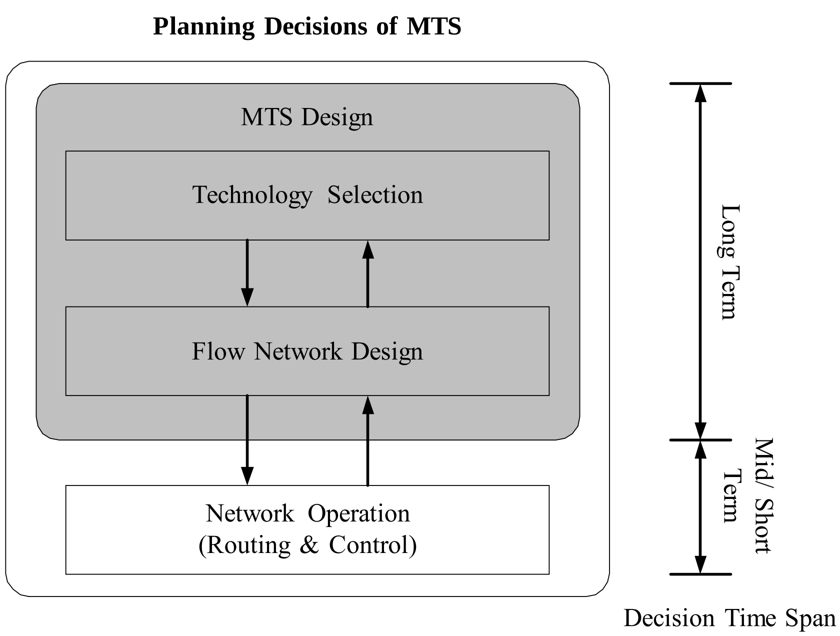

Figure 1-2: Intra-dependencies in MTS Design

1.3 Scope of the Thesis

This research focuses on the long-term decision making in the planning of MTS design. We first state the material transport system design problem (MTSDP) informally as follows:

Given a set of *tasks*, a set of *technologies*, and the *layout graph* of a manufacturing facility, the MTSDP is to assign tasks to technologies, such that a set of subsystems optimizes the *objective*, subject to a set of *constraints*.

The questions that the MTSDP intends to answer are as follows:

- Which task(s) should be assigned to which transport technology?
- What are the flow networks of selected technologies to serve their designated task(s)?
- How should the selected technologies and their flow networks be accommodated in the manufacturing facility?

1.3.1 Tasks

Throughout this thesis, we refer each transport request as a *task* that can be described by a set of attributes. Some specific attributes are part number, and input and output locations. Two tasks are considered to be identical if these attributes are the same. Thus, different requests of the same part number from the same input point to the same output point are combined into one task with aggregate requirements.

The required attributes can be derived from manufacturing engineering and plant data. The details of data extraction and prototyping techniques can be found in Sharp, Ram et al. (2000) and Everette (2000).

1.3.2 Technologies

The term *technology type* is used to denote the specific type of material transport technology. For example, counterbalanced forklift truck and narrow-aisle lift truck are two different technology types. For the detailed descriptions of commonly used technology types in manufacturing, the reader can refer to the tutorial web pages prepared by the College Industry Council of Material Handling Education.

The term *technology instance* (technology in short) is used to distinguish equipment belonging to the same technology type but with different specifications. For example, a counterbalanced forklift truck with load capacity of 3000 lbs and one with load capacity of 6000 lbs are two different technology instances.

1.3.3 Layout Graph

The layout graph is defined by a finite set of nodes and edges. The nodes represent the input/output points of a workstation, the intersections of workstation boundaries, and the column positions of a facility. The edges represent the boundaries of workstations in the facility. Note that the column positions are not restricted to boundaries of workstations. The layout graph provides an underlying structure for flow network construction of material transport technologies.

1.3.4 Task-resource Combinations

The material transport system requires different types of resource to satisfy the transport requests. The major resource types considered in the design of the MTS system are: material transport technology, space, and capital. Tasks are the driving force for the formation of a resource combination. Each *tasks-resource combination* forms a subsystem to serve a specific set of tasks.

1.3.5 Constraints

There are various types of constraints on the construction of a material transport system, which can be organized as follows:

- Compatibility

  Compatibility indicates whether a technology is physically capable of serving a specific task or not. To answer this question, extensive comparisons between the task attributes and technology specifications need to be made. Detailed descriptions of task attributes and technology specifications are discussed in Section 3.1.

- Network restrictions

  Network restrictions are used to characterize the transport behaviors of technologies and impose requirements on each technology on one of the layout graph variants so that the technology can form its own network to serve the designated tasks. Network restrictions are different in terms of technology. However, these constraints can be classified into three major categories, connectivity, capacity, and directionality constraints. The detailed descriptions of these three types of constraints for each technology are discussed in Section 3.3.

- Availability

  Availability constraints concern the limited nature of different types of resource. The major availability constraints on MTS design problem are:

  - Capital budget – The MTS design involves long-term capital investments. It is usually the case that there is a capital budget imposed by the management.
  - Space (Width) – There is a restriction on the width of the space used by the selected technologies.
  - Space (Conflict) – For some technology types, their installations might exclude other types in the same space, e.g., overhead conveyors and crane technologies.
  - Technology – The technology or its size might be (partially) pre-specified by the management. This typically happens in applications of redesigning the MTS.
- Assignment

  The assignment constraints make sure that each task is served by exactly one technology.

1.3.6 Objective

The objective is used to measure the goodness of a MTS design. The objective considered in this research is lifetime cost minimization. The major cost categories considered are investment costs and operating expenses.

1.4 Goals of the Research

The goals of this thesis are two-fold. First, we aim to provide an integrated decision framework for material transport system design. In the literature, the researchers tend to treat the design decisions of MTSDP as stand-alone problems; the consequences of this separation will be pointed out later. Moreover, considering the role of MTS design in manufacturing facility layout planning, we need to make sure that the proposed decision framework characterizes the space requirements of technology flow.

The second goal of this thesis is to contribute some modeling and algorithmic accomplishments based on the proposed framework. The MTSDP is a combinatorial problem. Therefore, some specific problems within the MTSDP can be modeled and solved by combinatorial optimization techniques.

To explore the MTS design problem we make the following assumptions.

- The layout graph of a facility is given, as indicated in Section 1.3.3.
- The input and output points of a workstation have enough capacity so that starving and blocking do not occur at these points.
- The set of technology instances is finite and the information for each technology is known.
- All material is transported by unit load. The size and volume of a unit load depend on the technology.
- The information for each of a finite set of tasks is known: origin, destination, attributes of material to be transported, and quantity to be transported.

CHAPTER 2

REVIEW OF BACKGROUND LITERATURE

MTS design is one of the most important aspects of manufacturing facility design. From the perspective of MTS design, the fundamental questions that need to be answered are what transport technologies are going to be used in a manufacturing facility and how will they be used. Previous literature usually separate the MTS design problem into the technology selection problem and the flow network design problem. For ease of discussions, the review of literature is organized following this division.

2.1 Background of Technology Selection

Technology selection is the one of the earliest decisions that needs to be made for the design of intra-facility transport system. The technology selection problem studied in the literature can be informally stated as follows:

Given a finite set of technologies and their specifications, a finite set of tasks and their attributes, and the design criteria, the technology selection problem is to best match the tasks and technologies such that each task is served by exactly one technology.

The solution approaches used for the technology selection problem are quite diverse. They range from simple check sheets to decision science, expert systems, and sophisticated mathematical programming models. The literature survey is organized based on the solution approach.

2.1.1 Check Sheets

Apple (1972) proposed a 9-step sequential procedure for facilitating the technology selection process. This procedure is one of the earliest and the most influential works to deal with this complex and difficult problem. The proposed procedure is basically a matching process between task attributes and technology specifications. Several principles, guidelines, criteria, and evaluation sheets are developed for matching qualitative factors in different level of details. Having narrowed the selection to a few technologies, the author suggests a careful evaluation of the cost associated with each alternative, and a check of compatibility between technology types under consideration with other technologies in use, or to be used. Then, the selection of the specific technology type can be made based on the preceding analyses.

In order to evaluate the cost of each alternative and help the decision makers get started in selecting the appropriate technology, Kulwiec (1980) provides operating characteristics, application notes, cost factors, and approximate prices for basic technology types. A user interactive selection procedure for automated guided vehicle (AGV) was proposed by Shelton and Jones (1987). The first step of this procedure is to get the specifications of the AGV based on the requirements of a specific manufacturing plant. The second step is to choose a set of specifications against which technologies will be evaluated using a weighting procedure. A list of attributes for the selection of AGV systems is proposed, and an illustrative example is given to demonstrate the procedure.

Chu (1995) proposed a two stages computer-assisted system for selecting material handling technology. The first stage identifies the candidate technology list through the use of subjective ratings on technology specifications in terms of their relevance to tasks, and the calculation of a normalized score of accumulated rating for each technology type under consideration. The candidate technology list is built by accepting technologies whose normalized score exceeds a pre-specified minimum acceptance level. Then, the evaluation of candidate technology is conducted by economic analyses. The proposed criteria include present value, return on investment, and payback period method.

2.1.2 Expert Systems

An expert system consists of computerized routines that are intended to mimic the reasoning process of a human expert. This solution approach is produced by the coded domain knowledge and heuristics. Expert systems used for selecting material transport technology consist of four major components: a knowledge base, a user interface, an inference engine, and a performance evaluation approach.

A knowledge base is constructed for storing the specifications of technologies, which are usually compiled from material handling related literatures, such as Apple (1972), Apple (1977), Tompkins, White et al. (1996), . . . etc. This domain knowledge is represented by a set of rules, such as IF-THEN statements. The user interface is designed to glean the task attributes from the user in an interactive manner. The inference engine serves as a logical matching mechanism between task attributes and technology specifications. This matching mechanism generates queries adaptively, based on users' answers of previous queries. After multiple alternatives survive at the end of this reasoning process, a performance evaluation approach is applied to make a selection based on the pre-specified criteria.

Fisher, Farber et al. (1988) proposed an expert system (MATHES) that selects the appropriate types of material handling technology for intra-facility moves of unitized material. A set of user-assigned weights associated with each selected technology type is used to evaluate the appropriateness of technologies for tasks. In their example, the authors also consider the acquisition cost of technology in order to make the selection not only technically feasible but also economically efficient.

Malmborg and Agee (1987) presented a prototype expert system for industrial truck type selection. The authors define an industrial truck type as a collection of attributes that specify truck types in sufficient detail such that one or more commercial models could be associated with it. They use the task attributes to specify an ideal technology. Then, the selection of technology simply becomes a comparison of the ideal technology with commercially available technologies. Based on a similar idea and procedure, Luxhoj and Hellman (1992) developed a prototype expert system for AGV selection.

Gabbert and Brown (1988) and Gabbert and Brown (1989) constructed a prototype expert system for selecting and configuring the technologies that store and transport materials in the facility. The proposed model, MAHDE, aims at generating acceptable material handling systems based on preferential and operational knowledge. Operational knowledge is constituted by a set of rules and used for generating acceptable selections. Preferential knowledge reflects the acceptability measures of selections. This knowledge is obtained by decision analysis techniques, and it is used for searching the most preferable selections or generating improvements from current selections. An example is given to illustrate the proposed procedure.

Bookbinder and Gervais (1992) developed an expert system for their four-step approach of selecting the best-fit material handling technology. The first step involves selecting the basic technology type. Technologies whose basic type meets the initial rules are retrieved in the second step. The compatibility of these technologies is compared with task attributes. The list of candidate technologies is further narrowed in step three by eliminating those whose specifications do not meet physical restriction imposed both by tasks and facility requirements. A multi-attribute decision-making (MADM) approach is applied to calculate the closeness of each candidate technology to the ideal technology derived from task requirements. In case there is no ideal technology, the MADM will recommend the technology whose performance is closest to the ideal.

Matson and Mellichamp (1992) gave a detailed description of constructing a knowledge base for selecting and configuring material transport technologies. The authors also developed an expert system (EXCITE) suitable for the technology selection of discrete parts transportation in a manufacturing facility. For tasks with multiple technology alternatives, EXCITE applies a weighted evaluation technique to select the most preferable technology based on pre-specified criteria.

ICMESE, Park (1996), is built for selecting handling technologies that are suitable for transport, storage, and warehousing of materials in a manufacturing facility. Except for the common components used for the expert system, ICMESE also possesses the ability to select the most favorable commercial model by a MADM method, and evaluate its performance by a simulator. The output of ICMESE is a set of specific commercial models, ranked by priority, and performance measures of these commercial models.

Chan, Ip et al. (2001), proposed a method to develop a material handling equipment selection advisor (MHESA). This expert system contains an analytic hierarchy process (AHP) model to evaluate the performance of feasible commercial models and recommend the one with the highest ranking.

2.1.3 Mathematical Programming

Another line of research focuses on the economic efficiency of technologies. Webster and Reed Jr. (1971) proposed a binary integer programming formulation and an algorithmic procedure for the selecting the material transport technology. The objective of their procedure is to minimize the sum of investment cost, operating cost, and changing unit load cost, where the possible unit load changes are pre-specified. The authors proposed a heuristic algorithm to solve this problem. This algorithm first assigns individual tasks to technologies based on partial costs. The improvement of initial assignments is first done by interchanging the assignments of task and technologies to increase utilization levels. The second technique is to reduce the number of different technology types in order to reduce total fixed costs. The largest example reported in this article contains 10 technologies and 300 tasks.

Hassan and Hogg (1985) pointed out that the algorithmic approach proposed by Webster and Reed might be computationally expensive. Therefore, they presented a construction heuristic to obtain feasible solutions quickly for a similar problem but without changing of a unit load. The authors developed a technology-centered algorithm: for each technology considered, the algorithm first calculates the cost required for serving all compatible tasks. A cost allocation scheme is used to determine an index value, or average cost per task, for all tasks that are unassigned. The assignment then proceeds greedily by using these average costs per task. Once the utilization rate of a technology reaches a target value, the index values for the remaining unassigned tasks are recalculated, and the process continues with the next efficient technology until all tasks are assigned. The proposed algorithm is compared with Webster and Reed's on the same examples. The published results show that the solution qualities of the two algorithms are similar. However, the algorithm proposed by Hassan and Hogg (1985) might require less computational effort. Heragu (1997) reported a mixed integer programming formulation, which is similar with the formulation of Hassan and Hogg (1985), except for the consideration of the underlying layout. A small example is given and solved by commercial solver.

Kouvelis and Lee (1990) modeled the problem of material transport technology selection and specification in a different manner, similar to Jones (1971). Each workstation is treated as a node and the compatible technologies of a task are modeled as arcs connecting nodes. The resulting formulation becomes a parametric, minimum convex-cost multi-commodity flow problem on a multigraph. The computational experiments are done using a MINOS subroutine to obtain exact solutions and the heuristic described by Steenbrink (1974) to obtain approximations. The reported deviation from the optimal solution for the heuristic is less than 5% for 15 randomly generated examples.

2.1.4 Hybrid Approach

Combining expert systems and mathematical programming, Fisher and Maimon (1988) proposed a two-phase decision model for specifying and selecting robotic technologies. The first phase prescribes the specifications of technologies by analyzing the requirements of a given set of tasks. The second phase selects the appropriate and available technologies based on the descriptions specified in the first phase. An example is presented for illustrating the proposed solution framework.

Welgama and Gibson (1995) combined expert systems and optimization for automating the selection of material transport systems. A knowledge base is employed for analyzing the compatibilities of tasks and technologies. After this initial screening process, the compatible task-technology combinations are entered into an integer programming model that is an extension of Hassan and Hogg (1985). Besides investment cost and operating cost, the authors also include the cost of space, which is considered as a homogeneous resource. The first phase of the optimization is to find the minimum cost technology for each task without considering utilization; in the second phase the algorithm seeks to maximize the utilization of selected technologies by combining tasks. An example involving 16 technologies and 112 tasks was solved to demonstrate the approach.

2.1.5 Discussion

To facilitate our discussion on the surveyed literature, the modeling and solution characteristics of some selected works are summarized in Table 2-1, respectively. Each column of Table 2-1 records the considered characteristic of the proposed models and solution approaches in the selected literature. The interpretation of each characteristic is summarized as follows:

- Origin-destination (O-D) Definition: According to Sinriech (1995), there are three types of origin-destination definition. The first one is the centroid-to-centroid (C to C). The second type is the output-to-input points, and the last one is the aisle-network obtained from the layout. The output-to-input points and aisle-network

O-D definition are suitable for certain technologies; however, the centroid-to-centroid distance measure is less representative of actual travel distances.

- Distance Metric: This characteristic indicates the distance metric used. The commonly used distance metrics in the technology selection literature are Euclidean, Rectilinear, and Chybechev metrics. The aisle-network distance can be considered as another distance metric.
- Empty Travel: The empty travel column records whether the approach considers empty flows explicitly or not.
- Conflict Resolution: This column describes the method of allocating limited resources in each model.
- Objectives: The objectives column summarizes the criteria used for selecting technologies.
- Solution types: This column indicates if the selection is restricted to single technology single task solutions (one-to-one) or allows single technology-multiple tasks solutions (one-to-many).
- Solution Techniques: This column summarizes the methods used for solving the selection problem in each model.

Table 2-1: Modeling and Solution Characteristics of Selected Literature on Transport Technology Selection

Literature	O-D Definition	Distance Metric	Empty Travel	Conflict Resolution	Objectives	Solution Type	Solution Techniques
Malmborg (1990)	C to C	Euclidean	No	N/A	Cost and Compatibility	One to One	Certainty Factor Calculus
Shelton and Jones (1987)	N/A	N/A	No	N/A	Multi-Objective (Unspecified)	One to One	User Ranking
Gabbert and Brown (1989)	N/A	N/A	No	N/A	Multi-Objective (Unspecified)	One to One	ES & Multiple Attributes Utility Theory
Bookbinder and Gervais (1992)	N/A	N/A	No	N/A	Cost, Distance…etc.	One to One	ES & MADM
Matson and Mellichamp (1992)	C to C	Euclidean	No	Subjective	Cost, Flexibility, Maintenance	One to One	ES & User Ranking
Chu (1995)	N/A	N/A	No	Subjective	Cost and Compatibility	One to One	ES, User Ranking & Economic Analysis
Park (1996)	N/A	N/A	No	Subjective	Cost, Technical & Strategic criteria	One to One	ES, MADM & Simulation
Chan, Ip et al. (2001)	N/A	N/A	No	Subjective	Cost, Performance, Technical & Strategic criteria	One to One	ES & AHP
Webster and Reed Jr. (1971)	C to C	Euclidean	No	Subjective	Cost (investment, operation, changing unit load)	One to Many	Heuristic Algorithm
Hassan and Hogg (1985)	C to C	Euclidean/ Rectilinear	No	Subjective	Cost (investment & operation)	One to Many	Heuristic Algorithm
Kouvelis and Lee (1990)	C to C	Euclidean	No	N/A	Cost (investment, operation, reliability & WIP)	One to Many	Commercial Solver & Heuristic Algorithm
Welgama and Gibson (1995)	N/A	Euclidean	No	N/A	Cost (investment, operation & space)	One to Many	Heuristic Algorithm

2.2 Background of Flow Network Design

Flow network design has significant influence on the characterization of technology flow within the facility, cost approximation of the selected technology, and the response time of carriers to transportation requests. The flow network design problem studied in the literature can be informally stated as follows:

Given 1) the underlying network and associated parameters, 2) specification of the technology under consideration, and 3) a set of tasks. Decide A) Arcs to be included in the resulting network, B) the orientation of each selected arc, and C) the flow on each selected arc, such that the sum of costs is minimized.

The following literature reviews are summarized according to the focus area in flow network design.

2.2.1 Flow Network Design for Carrier Requirements

In this section, we review techniques other than simulation used in the early design phase for estimating the number of carriers required. For some technology types, specifically carrier-based technology, the empty travel accounts for a significant part of the operation time. This portion of operation time is not as certain as loaded travel, because the empty travel is also affected by short-term operational decisions. To accurately capture the empty travel using simulation, the technology must first be chosen; the network must be designed; and the control policy on the designed network must be specified. In the stage of technology selection and flow network design, the large number of alternatives simply makes detailed simulation impractical. Therefore, a simple (in terms of information required) analytical technique is needed to incorporate the effect of empty travel in the early design phase.

Several researchers recognized this need and presented their approximations. Maxwell and Muckstadt (1982) first proposed an approximation based on the idea of the *netflow* at each workstation. The netflow at a workstation is the difference between the incoming flow and outgoing flow. This netflow is then treated as supply or demand of empty travel and modeled as the well-known transportation assignment problem. Intuitively, an empty carrier supply will tend to be assigned to the nearest empty carrier demand by the nature of transportation problem. This problem ignores the timing of supply and demand. Therefore, people in related research areas usually refer to this technique (M & M in short) as the best-case approximation.

Contrary to the idea of the best-case approximation, Malmborg (1990) developed a technique to obtain the "worst-case" approximation of empty travel. Given the supply and demand of netflow at each workstation, an empty carrier will be assigned to a farthest workstation that demands empty carriers. The author claimed that the actual empty travel distance is a weighted average of the best- and worst-cases. In order to obtain an approximation between the best- and worst-cases, Rajotia, Shanker et al. (1998) modified the transportation problem in Maxwell and Muckstadt by imposing upper bounds on flow at the nearest workstation.

Beisteiner and Moldaschi (1983) proposed two simple equations for empty travel approximation. The first one (BM I in short) also applies the idea of netflow and takes the product of average loaded travel distance and netflow as the approximation of empty flow. The second one (BM II in short) simply takes the total loaded travel distance as the approximation of the empty travel distance. These two techniques implicitly assume that the loaded travel is a good indicator of the empty travel.

In the same conference as Beisteiner and Moldaschi, Kuhn (1983) utilized the idea of factoring to approximate the empty travel. The possibility of an empty travel assignment is approximated as the proportion of a workstation's loaded travel requirement to the total loaded travel requirement. Therefore, the destination of empty travel of a carrier is not restricted to the nearest request as proposed by Maxwell and Muckstadt, nor the farthest request as proposed by Malmborg.

Besides loaded and empty travel, the carriers might experience waiting and blocking because of unsynchronized supply/demand, and heavy traffics. Due to the interactions among the variables involved, there seems to be no quantitative method to approximate this portion of time. However, there do exist some factors obtained from empirical studies to approximate the carrier waiting or blocking time. Kulwiec (1982) and Kulwiec (1984) used 0.2 to 0.4 and 0.15 to approximate empty travel time and waiting/blocking time, respectively. Koff (1987) proposed a facility-dependent (0.1 to 0.15 of total loaded travel time) empirical factor (KB in short) to approximate both idle waiting and blocking time.

Given the selected technology and its network, Egbelu (1987) conducted simulation comparisons for some of the aforementioned (BM II, Koff, BM I, Kuhn) techniques under different dispatching policies and load size (load per shift) for AGV system. In a specific aisle network, the results show that the four techniques generally under-estimate the carrier requirement. The results also show that the KB technique is inadequate in almost all experimental settings, while Kuhn's technique matches the vehicle requirements provided by simulation for several dispatching rules.

To account for shop floor dynamics, Bakkalbasi (1990) applied queuing theory to estimate the performance of some dispatching rules. The author assumed that the transportation requests at each workstation follow a Poisson distribution; the service times for each request are general distributed with finite first and second moments. The system is approximated by an M/G/c queue, where c stands for the number of carriers. The delay caused by congestion is approximated by a carrier delay factor. The author evaluated oldest-load-first (OLF), closest-load-first (CLF), closest-load with time priority (CLTP), and further-load-first (FLF) dispatching. The author obtained the following relation for empty travel time under different dispatching rules: CLF, CLTP, OLF, FLF (non-decreasingly ordered). The author also points out that elaborate dispatching rules are not likely to improve system performance significantly, and flow network design might be the way to enhance system performance.

In a multiple, re-circulating loop, unidirectional AGV network, Rajotia, Shanker et al. (1998) presented simulation comparisons for techniques dealing with load sensitivity, and criticality of material handling resource. According to the simulation studies under various load sizes and the criticality ratio proposed by Kim and Tanchoco (1993), the authors concluded that Kuhn, BM II, Kulweic, and RSB provide the carrier requirements approximately the same as results obtained by their simulation experiments.

Regarding the inclusion of empty carrier flow in network design, Sun and Tchernev (1996) gave a comparative study on a unidirectional aisle network system. Adding Maxwell and Muckstadts' empty flow approximation to their formulation, the authors compared the results by solving (1) loaded travel only, then obtaining the optimal empty flows, (2) loaded travel with pre-assigned empty travel by shortest path, and (3) loaded travel with simultaneous empty travel. The computational results of two examples show that the network obtained by the third scenario is the only method producing optimal solutions. The first scenario gives longer travel distance because it ignores empty travel in the network design phase. Note that the empty flow approximation of Maxwell and Muckstadt is distance dependent. The pre-assigned empty travel is based upon shortest distances given by the underlying network, not the designed network. Therefore, these results are reasonable for the use of Maxwell and Muckstadts' approximation. In a reported instance with a network of 31 edges; the resulting networks of scenario 1 and 2 have 11 edges different from the resulting networks of scenario 3.

Sinriech and Tanchoco (1992) employed a multi-criterion optimization model to determine the carrier size of an AGV system while explicitly considering the cost and throughput requirement. The proposed procedure is basically a trade-off analysis of throughput requirements and fixed costs of the AGV system by iteratively adjusting the weights associated with these two objectives. The authors argued that the throughput is a concave function of carrier size. In order to employ standard approaches, constraint linearizations are performed and approachable throughputs of carrier sizes are tabulated. The obtained carrier size can only be treated as a lower bound because routing issues are not considered.

Given the network of a specific vehicle-based technology and assumptions of the steady state task requirements, Herrmann, Ioannou et al. (1999) minimize the acquisition and operating costs of a vehicle-based technology. The authors proposed a linear integer program model and employed two sets of binary variables to represent the status of transport technology and the linkage of tasks. By these variables, the authors decide the number of required carriers, the assignment of tasks to carriers, and the time required by a carrier to traverse its route. Due to the complexity of this problem (NP-Hard by referring to vehicle routing problem), they proposed two heuristics and made worst-case analyses. The first approximation algorithm, with time complexity $O(n^2)$ where n denotes the number of tasks, is a greedy method. The tasks are first matched by minimizing travel time. According to this travel time, assign these tasks to a carrier using a nearest neighbor approach until capacity is reached. The second approximation algorithm, with time complexity $O(n^3)$, first solves the matching of the transformed problem, and then solves the bin-packing problem by a first-fit-decreasing heuristic. According to the reported computational results for randomly generated instances, the first heuristic has better performance with the number of carriers used, and the second heuristic outperforms the first one in terms of variable cost. The accuracy of both heuristics is improved as the number of tasks increases.

A recent work, Vis (2002), studied the problem of determining the minimum number of vehicles required to transport all tasks within time windows. The author considered a general manufacturing facility with fixed shop floor storage capacity for each workstation. The release time of each job is defined as the point in time at which the job is processed and released to storage. The processed jobs in storage must be transported before the saturation of the storage space. The time window associated with each task is the time period between its release time and latest pickup time. In order to determine the required carrier size, the author proposed a network representation by dicretising the time windows and creating multiple copies of nodes. The arcs in the resulting network represent the feasibility of servicing two tasks by one carrier. In this network, a path represents a feasible schedule of tasks to be transported by one carrier. A search algorithm is employed to enumerate all possible paths. Then, a set partitioning formulation is modeled and solved to obtain the minimum number of paths (carriers).

2.2.2 Flow Network Design on Aisle Network

Aisle network design accounts for the majority of the literature in the domain of flow network design. The major users of aisle networks are vehicle-based technologies. The distance is measured from the output to the input points along a given aisle network. Two constituents of the cost structure are fixed cost associated with the inclusion of arcs, and the variable cost that varies with the flow intensity. If we treat each task as a distinct commodity, the resulting problem can be modeled as a variation of the fixed charge network design problem (See Magnanti and Wong (1984), and Minoux (1989)).

Several researchers have studied the flow network design problem given the included arcs in an underlying network (Flow Network Design Problem given A). Gaskins and Tanchoco (1987) proposed a binary integer programming formulation for this problem. Vekataramanan and Wilson (1991) proposed an improvement by imposing connectivity constraints with a compact formulation and a specialized branch-and-bound procedure. Kouvelis, Gutierrez et al. (1992) provided five heuristics, including simulated annealing algorithms, for this problem. The computational results indicate that composite heuristics yield solution quality comparable to that obtained by simulated annealing algorithms.

Bakkalbasi (1990) studied flow network design on aisle network. A variant of a node arc formulation for the fixed charged capacitated multi-commodity network design problem is proposed for the flow network design problem for AGV systems. Due to the inherent problem complexity, the author developed three heuristics based on relaxations for obtaining feasible solutions. The basic idea of the GRID heuristic is to construct a convex hull based on the geometric dispersion of tasks. The connectivity restriction is satisfied by re-orienting the arcs. The PATH GENERATION heuristic relaxes the flow capacity and ignores the path building cost. The weight associated with each commodity is obtained by solving the all pairs shortest path problem, and then greedily assigning the commodities based on weighted distance. The last heuristic for path flow network construction, ARC DELETION, starts with the underlying network. Based on the idea that a busier section should be on a shorter path, this heuristic proceeds by deleting arcs in a greedy sense. All three heuristic are able to generate feasible flow path networks. For further refinement, the author proposed standard network improvement procedures based on arc additions, deletions, and re-orientation.

Sharp and Liu (1990) considered the construction of shortcuts between stations and the allocation of spurs at each input/output point in a fixed-path, closed loop material transport system with congestion of carriers. The congestion at each station is modeled by nonlinear cost curves, which are functions of the number of carriers moving past a station, including carrier costs and construction costs of the spur. These cost functions are developed from queuing theory and the results are validated by simulation studies. In order to alleviate the congestion caused by loading/unloading operation and to reduce travel distances, the design decisions are building spurs/shortcuts or not. A piecewise linearization technique is used to approximate the nonlinear cost functions and a linear mixed integer programming formulation is constructed to serve as a selection tool. Two examples are tested for the proposed procedure. The results show that considering carrier congestion in the flow network configuration yields a better and more accurate design, before proceeding to simulation.

Herrmann and Ioannou (1996) consider the design of a flow network in a discrete parts manufacturing facility. The authors formulate the MTS network design on an aisle network similar to the model proposed by Bakkalbasi but without the directionality constraints. Two efficient heuristics are proposed to determine near-optimal solutions to the NP-hard problem. The basic idea of the first one, called fixed-charged adjustment heuristics (FCAH), is to iteratively adjust the arc fixed costs and selectively include arcs until a feasible network is obtained (based on LP relaxation). The second one called state space search heuristics (SSH) ranks binary variables with respect to their distance to 0.5 by solving the LP relaxation. Arc inclusion and exclusion is based on their closeness to 1 or 0. The heuristic then proceeds with the fixed arcs to solve the LP relaxation. For small instances, the authors compared the FCAH and SSH with optimal solutions obtained by commercial optimization software. Instances with up to 30 arcs are solved, and the two heuristics yield solutions that deviate from optimum by 3.2, and 3.6 percent, respectively. For larger instances, the authors compared the FCAH, and SSH with the lower bound provided by dual ascent and LP relaxation. Instances with up to 60 arcs are solved, and the two heuristics yield solutions that deviate from optimum by 7.9 to 10.3 and 8.2 to 10.4 percent, respectively.

2.2.3 Variations of Flow Network Design on Aisle Network

Aside from the requirements-driven network design models mentioned above, one line of research studies the performance of a specific material transport technology, the AGV system to be exact, in some specialized network topologies. The reported specialized topologies are shown in Figure 2-1. Figure 2-1(a) is a topology on an aisle network that is typical in the survey of the previous section, Figure 2-1(b) presents a loop topology, Figure 2-1(c) depicts a tandem loop topology, and Figure 2-1(d) gives a topology based on segmented flow technology.

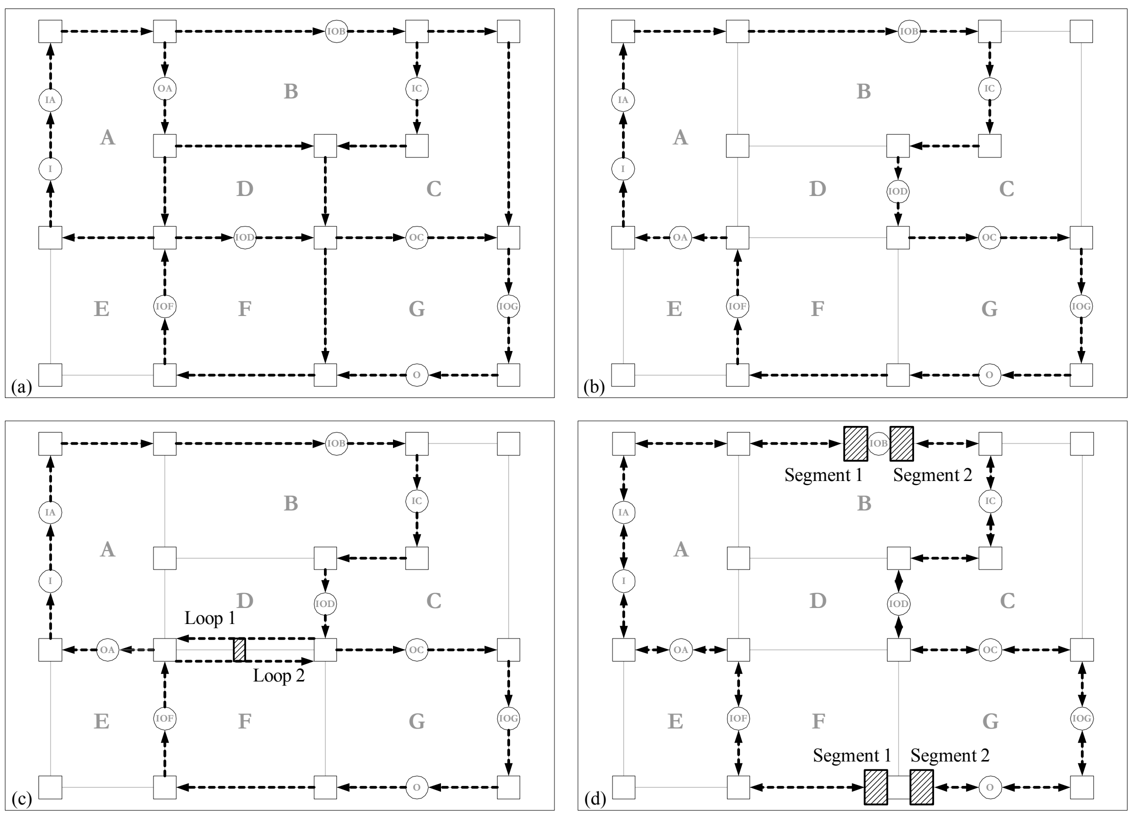

Figure 2-1: Variations of Aisle Network Design

Given a block layout, the optimal single loop network design is first proposed by Tanchoco and Sinriech (1992). Sinriech and Tanchoco (1993) proposed a mathematical programming formulation and developed an efficient solution approach for this problem.

Asef-Vaziri, Dessouky et al. (2001) proposed an alternative formulation and solution procedure for the same problem as Tanchoco and Sinriech (1992). The authors focus on developing a better formulation in terms of LP relaxation, analyzing the mathematical properties, and developing a branch-and-bound solution approach. The proposed computational methods are tested on two sets of instances by standard commercial software. The authors also show the computational efficiency of the proposed method by comparing it with other approaches.

Asef-Vaziri, Laporte et al. (2000) and Asef-Vaziri and Laporte (2002) studied the problem for constructing a shortest loop such that at least one of the boundaries of each workstation is included in this loop. This research is focused on the formulation and solution approach of the proposed shortest loop problem (SLDP) for the design of material transport system in factories. The authors modeled the problem as a binary integer program, where the objective is to minimize the loop distance. The design issues are to determine which nodes and edges should be included to form a loop in the underlying block layout. A compact formulation is proposed, and the authors exploit the problem structure to take the advantage of properties of the block layout. Three simplification procedures are developed to reduce the number of constraints so that small or moderate-size (up to 40 workstations) instances can be solved by standard commercial software without decomposition or relaxation. For a detailed review on loop topology in flow network design, the interested reader can refer to Asef-Vaziri and Laporte (2002).

The tandem topology is invented based on the divide-and-conquer principle. The tandem topology partitions workstations into several single-vehicle, non-overlapping zones. Additional interface stations are required to connect zones and transfer the cross-zone traffic. Bozer and Srinivasan (1991), and Bozer and Srinivasan (1992) invented this topology and proposed a partitioning heuristic to configure the tandem topology. The proposed heuristic consists of three phases. The first phase is to generate subsets of workstations by a geometric heuristic of the traveling salesman problem. Each generated subset defines a zone. The second stage is to check the throughput feasibility of each zone by a closed form. The third stage is to apply a variation of a set-partition model with a load-balancing objective to choose a configuration from the feasible zones. The authors present a comparative study between the proposed and conventional topologies. Simulation results show that the tandem topology outperforms the conventional topology in terms of throughput. However, Sinriech (1995) points out that the physical aisle structures used in this comparative study are not identical.

To reduce the sensitivity of tandem topology to vehicle failure, Ventura (2002) studied the tandem system with multiple vehicles. Intuitively, workstations with short distances and large flow volume between them should be assigned to the same zone such that both intra-loop travel and inter-loop travel can be reduced. This argument is used to develop a heuristic clustering algorithm for partitioning the workstations. Sinriech and Tanchoco (1995) proposed the segmented flow topology, constructed by non-overlapping single carrier segments. This method can be applied to divided loops, as in Sinriech, Tanchoco et al. (1996) or a tree topology divided into segments, as in Sinriech and Tanchoco (1995). At both ends of each segment, transfer buffers serve as input and output for the carrier segment.

2.2.4 Flow Network Design on Other Working Networks

Compared to the MTS network design research on aisle networks, research on other types of working networks is rare. Proth and Souilah (1992) provided a fast branch-and bound algorithm for finding the shortest path between two workstations. This method may serve as a tool to construct some working networks, e.g., conveyor networks. Montreuil and Ratliff (1989) applied the cut-tree algorithm to create a minimum weight spanning tree. The nodes and edges of the resulting tree represent the output or input points, and flow path segments, respectively. The weight associated with each edge indicates the flows assigned to each edge. The flow network with minimum material transport cost is determined by adjusting the lengths of edges so that the cumulative product of flows and edge length is minimized. This method is topology specific: it only works for a spanning tree structure. Some technology classes might be suitable for this topology, e.g., manual-driven vehicles or floor-level conveyors.

Chhajed, Montreuil et al. (1992) studied the flow network design problem with shortest rectilinear distance. The major applications of the proposed problem are for flow network designs that are not restricted to an aisle network; this situation is denoted as free flow. Given a directed network and a set of tasks, the problem is to find the minimum distance design by selecting arcs from the given network and deciding their flows. The authors formulated this problem as a mixed integer program. Lagrangian relaxation of the formulation decomposes the problem into separable shortest path problems. A heuristic is also given to cope with large instances.

2.2.5 Discussion

From the surveyed literature on flow network design, we summarize the results as follows:

- As shown earlier in this sub-section, there are three articles, Egbelu (1987), Bakkalbasi (1990), and Rajotia, Shanker et al. (1998), that study the performance of techniques other than simulation used in the early design stage for estimating the number of carriers required. Since the flows of loaded carriers are comparatively certain, they focus on the empty travel. Although the approaches used by these researchers are different, the conclusions regarding the performance of approximation techniques are quite consistent. The results of all approximation techniques are between the theoretical lower bound Maxwell and Muckstadt (1983) and upper bound Malmborg (1990). The factoring technique proposed by Kuhn (1983), named OLF in Bakkalbasi (1989), appears to be the most reasonable method to approximate the empty carrier travel in the early design phase. Kuhn's method is a distance-independent approximation; it implicitly assumes centralized control of carriers and a first-come-first-serve dispatching rule. The results of Kuhn's approximation provide a steady-state approximation. Some flow network design literature modifies the loaded from/to matrix based on Kuhn's idea so that the matrix accounts for both loaded and empty travel.
- For the articles on flow network design on an aisle network, there is a range of approaches from orienting arcs only to selecting and orienting arcs. One line of research is dedicated to exact solution approaches using implicit enumeration schemes, branch-an-bound. See Kaspi and Tanchoco (1990), and Kim and

Tanchoco (1993) for examples. The other line of research is devoted to developing efficient heuristics. See Bakkalbasi (1989), and Herrmann et al. (1995) for examples. Table 2-2 summarizes the modeling and solution characteristics of selected literature, respectively.

- The specialized topologies introduced in Section 2.2.3 are preferable under specific conditions. They are created primarily because of a concern for operational issues. The motivation for creating these topologies can be treated as a bottom-up approach from the perspective of MTS planning: proposing a topology because of its control efficiency. These specialized topologies can be used as patterns for configuring the flow network after MTS design. In this research, we emphasize providing a structured way for obtaining the desired material transport system based on requirements, not the other way around.
- The major users of an aisle network are vehicle-based technologies and some overhead conveyors. Regarding other technology classes with transport behavior not consistent with aisle network, there is a need for more research. Based on a survey by MHIA, Figure 2-2 shows the product shipments of four types of material transport technologies from 1997 to 2002. The material transport technologies considered in this research are covered in the first three categories: industrial trucks and tractors; hoists, cranes and monorails; conveyors and conveying equipment. Although the users of product shipments (e.g., manufacturing, warehousing, construction...etc.) are not available in this survey, we can observe that there is no single category that dominates over the past six years. Unfortunately, the percentage of research on flow network design does not

seem to reflect this fact, and the majority of research is focused upon technologies on aisle network, e.g., AGV system.

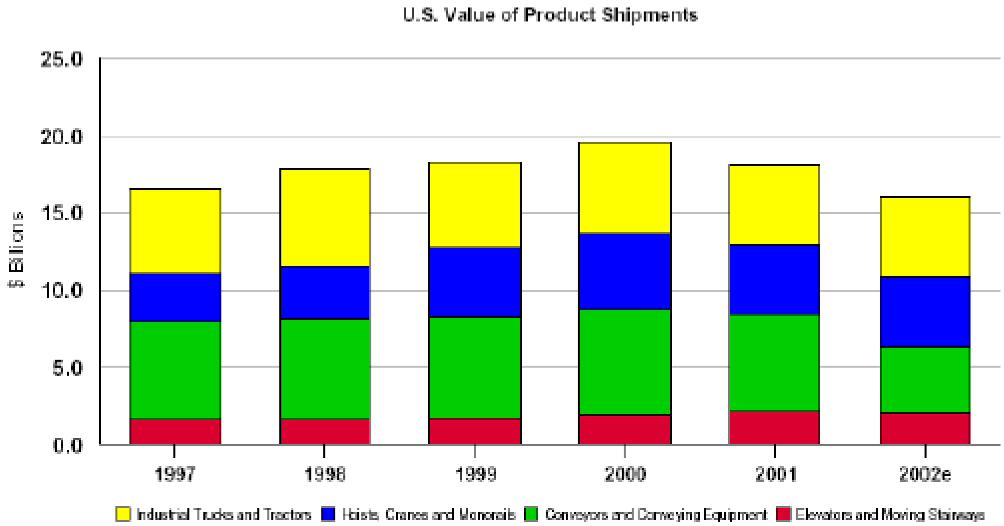

Figure 2-2: Product Shipments of Material Transport Technology (Source: MHIA)

Table 2-2: Modeling/Solution Characteristics of Selected Literature on Flow Network Design on Aisle Network

Reference	Network Restrictions			Empty Travel	Decision Variables			Objectives	Solution Techniques
	Connectivity	Capacity	Directionality		Arc Inclusion	Arc Orientation	Arc Flow		
Gaskins and Tanchoco (1987)	I/O Weak Connectivity	No	Yes	No	Given	Unknown	Unknown	Operation cost	Commercial Optimizer
Gaskins and Tanchoco (1989)	I/O Strong Connectivity	Yes	No	Kuhn	Given	Unknown	Unknown	Operation cost	Commercial Optimizer
Vekataramanan and Wilson (1991)	SCC	No	Yes	M & M	Given	Unknown	Unknown	Operation cost	Branch & Bound
Kaspi and Tanchoco (1990)	I/O Weak Connectivity	No	Yes	No	Given	Unknown	Unknown	Operation cost	Branch & Bound
Kouvelis, Gutierrez et al. (1992)	I/O Strong Connectivity	No	Yes	Kuhn	Given	Unknown	Unknown	Operation cost	Heuristics (Greedy, Simulation Annealing, Composite heuristic)
Sinriech and Tanchoco (1991)	I/O Strong Connectivity	No	Yes	Kuhn	Given	Unknown	Unknown	Operation cost	Branch & Bound, Heuristic
Kaspi, Kesselman et al. (2002)	I/O Strong Connectivity	No	Yes	M & M	Given	Unknown	Unknown	Operation cost	Branch & Bound
Kim and Tanchoco (1993)	I/O Strong Connectivity	No	Yes	Kuhn	Unknown	Unknown	Unknown	Fixed & Operation Cost	Branch & Bound, Heuristic
Sun and Tchernev (1996)	I/O Strong Connectivity	No	Yes	M & M	Unknown	Unknown	Unknown	Fixed & Operation Cost	Branch & Bound, Heuristic
Herrmann (1995)	I/O Weak Connectivity	Yes	No	No	Unknown	Unknown	Unknown	Fixed & Operation Cost	Heuristics
Bakkalbasi (1990)	I/O Strong Connectivity	Yes	Yes	Kuhn	Unknown	Unknown	Unknown	Fixed & Operation Cost	Heuristics

2.3 Background of Some Representative Solution Approaches

Webster (1969) presented a pioneering work on the economic material transport technology selection problem. The problem formulation and algorithms are briefly discussed in Section 2.2.2. We focus on the implications behind the proposed algorithms because of their impact in the literature. The main assumption of this work is that increasing utilization of selected technologies may lead to an economical selection. A task is initially assigned to a technology based on minimum cost based on the greedy principle. Versatile technologies, technologies that can serve more than one task, are then used to aggregate tasks based on a heuristic cost allocation scheme. If we treat the travel distance available per period of a unit of technology as a bin and each task (loaded travel only) as a weighted object (this abstraction might be the reason of the Bin-Packing formulation proposed by Hassan and Hogg (1985)), the maximum utilization of bins then becomes a surrogate objective of minimum number of bins used, and therefore, a minimum cost selection. However, there is a question of validity of this abstraction, the accumulated weights of objects (loaded travel), to represent the cost of serving tasks by a technology within a facility without the knowledge of the associate flow network designs.

Noble and Tanchoco (1993) proposed a concurrent design and economic justification procedure for the material handling system design. The authors advocate the advantages of considering economic trade-offs during the alternatives generation phase. The solution framework for their concurrent design procedure is like a classical branch-and-bound procedure in combinatorial optimization. Denote design alternatives as nodes in the branch and bound tree. Nodes at the same depth represent alternatives at the same level of detail. The alternatives generation, a branching scheme, is a composite of ranking processes with subjectively assigned weights from literature (expert systems) and the construction heuristic proposed by Hassan and Hogg (1985). A set of automatically generated models, capacity analyses, queuing networks, and simulation models are used to extend the non-dominated design alternatives to greater detail. Throughout the development of alternatives, a marginal analysis procedure (bounding scheme) is used to evaluate the economic performance of each alternative. An example based on the prototype implementation of the design procedure is reported.

Kouvelis (1988) proposed a two-level solution approach for the MTS design problem. The first level is for selecting and specifying the technologies, and the second level focuses on the topology designs of the selected technologies. The decision framework is a hierarchical process: the problems in the first level are solved and their solutions are treated as inputs to the second level. In order to separate the interaction between the technology selection and flow network design problem, the author uses an “activity network” (centroid-to-centroid measure) to represent the layout design. The first level problem Kouvelis and Lee (1990) is summarized in earlier work. For the second level, after the technologies are chosen, the networks of some technologies are then designed. Concave cost network design problems are introduced and their implications for the MTS network design are briefly discussed. Therefore, this solution approach still treats the MTS design problem as two separate problems, technology selection and flow network design problem.

2.4 Concluding Remarks

This background review is not meant to be a criticism of the surveyed literature; they were written for their own purposes. Because they help present a complete picture of the work that should be done in MTS design, some of them will be used extensively for the development of the proposed solution approaches. To summarize this background literature review, we propose two research topics within the subject of MTS design.

- Multi-technology flow network design

One of common assumptions in the flow network design literature is that there is single technology compatible with all tasks. Manufacturing is a set of processes that change the states of materials and transform the materials to final products. For the cases that a single technology is not able to meet the transport requirements and/or a single technology design is simply not economical, there is lacking a methodology to construct a multi-technology flow network that satisfies both task and system requirements.

- Integrated solution approaches for MTS design in general manufacturing applications

As shown in this review, the literature tends to separate the MTS design problem into two independent design decisions, technology selection and flow network design. In order to make each problem well defined, some simplifications and assumptions are made, e.g., centroid-to-centroid origin-destination distance technology selection, and a single technology compatible with all tasks in a manufacturing application for flow network designs. The drawbacks and limitations of this separation and the associated simplifications will be pointed out later. Whether from the perspective of facility layout planning or MTS planning, the separation into two stand-alone problems cannot suit the needs for general manufacturing applications. Therefore, integrated solution approaches for the MTS designs that recognize the differences between technologies and consider the system requirements are required.

CHAPTER 3

THE CHARACTERISTICS OF THE MTSDP

In this chapter, we further discuss the Material Transport System Design Problem (MTSDP) by illustrating important characteristics of it. This chapter is organized as follows: We briefly discuss the capabilities of transport technologies, and some typical task attributes and technology specifications are introduced in Section 3.1. In Section 3.2, we discuss the importance and the behavior of empty travel in the early design phase for some technology types. In Section 3.3, we propose a set of classification criteria for transport technologies commonly used in manufacturing environments and present technology classes for the MTSDP. Based on these characteristics and the interactions of decisions involved in the problem, we propose a general decision framework for the MTSDP in Section 3.4.

3.1 Task Attributes and Technology Specifications

One of the decisions in the MTSDP is the assignment of tasks to technologies. Although the latest transport technologies are designed to be as versatile as possible, some mechanical limitations of technologies still need to be respected. The task attributes and technology specifications primarily emphasize the mechanical abilities of the technology instances to perform the tasks.

Table 3-1 gives an example of individual task attributes and Table 3-2 gives some examples of technology specifications. Each row in Table 3-1 and Table 3-2 represents an attributes/specifications of a task/technology instance. These attributes/specifications are usually specified by a numerical value(s) (e.g., 500 lb.), a qualitative scale value (e.g., on a scale of 1 to 10), or a logic value (yes/no).

Table 3-1: Examples of Task Attributes (Sharp, Ram et al. (2000))

Task Attributes	Description
Pickup point	The coordinates (3D) of pickup point
Delivery point	The coordinates (3D) of delivery point
Quantity	Parts to be transported per time period
Weight	The weight per part
Size (per part)	The dimensions (3D) per part
Fragility	Whether the part is fragile
Suspended load	Whether the part is suspendable
Unusual shape	Whether the shape of part is unusual

Table 3-2: Examples of Technology Specifications (Sharp, Ram et al. (2000))

Technology Specifications	Description
Load weight	The load capacity of the technology instance
Load size	The load size of the technology instance
Lift height	The lift height of the technology instance
Suspend load	Whether the technology instance can handle suspended load
Unusual shape load	Whether the technology instance can handle unusual shape load

3.2 Technology Flows and Empty Travel

The *technology flow* (flow in short) is a measure of material flow by transport unit. It is obtained from unitizing the material flow into discrete flow units for a specific technology. For example, if the capacity of a forklift truck is 8 units, then a transport request with 40 parts can be unitized into 5 movements of forklift truck. Then, the flow of this transport request with the forklift truck is 5.

From the perspective of the MTSDP, the network activity includes not only the 5 movements of forklift truck from the origin to the destination of the transport request, but also the deadhead travel for these 5 movements to perform this service. Empty travel connects a pair of loaded travel for some transport technologies; say loaded travel 1 and 2. The non-productive activity travels from the destination of 1 to the origin of 2 to become available for the next loaded travel.

In Section 2.2.1, we discuss the literature of empty travel at the early design phase. We adopt the empty travel representation by Kuhn (1983) in this research. In general, Kuhn's representation takes the factored loaded travel as an approximation for the empty travel. For example, consider a material transport system (or sub-system) with two transport requests, 1 and 2. The flow requirements for these two requests are denoted as *F*1 and *F*2, and the origins and destinations of these two requests are denoted as *o*(1), *o*(2) and *d*(1), *d*(2), respectively. The network activity of this system (or sub-system) according to Kuhn's empty travel representation is provided in Figure 3-1. The solid line indicates the loaded travel from the origins to the destinations. The dashed lines denote the empty travel from *d*(1) to *o*(1), *d*(1) to *o*(2), *d*(2) to *o*(1), *d*(2) to *o*(2), with factored flows. Note that we have six tasks in this system (or sub-system) instead of two if the employed technology requires empty travel.

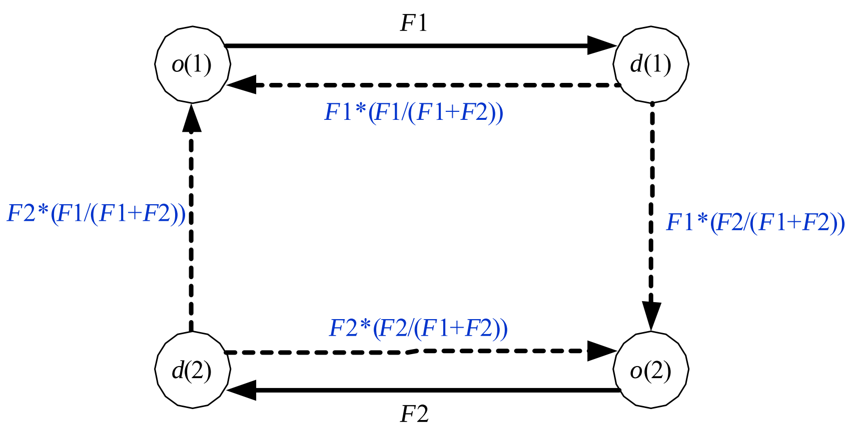

Figure 3-1: Example of Kuhn's Empty Travel Presentation

3.3 Technology Classes

In the domain of material transport system design, the transport technology plays a central role when a designer specifies various types of resources to satisfy the transport requirements. One of the challenges for the designers is the versatility of technologies.

Although each type of technology is built for its own purpose, the flexibility of technologies results in a significant overlap in terms of their functionality. From the perspective of design, we aim to derive a simpler structure for the transport technologies such that instances in the same class share the same properties. In order to do so, the following criteria associated with each technology type are considered below.

3.3.1 Network Level

The network level denotes the vertical level of space within the facility at which a specific technology is installed. The levels of space can be classified as:

- Floor level: The floor level is denoted for technologies that are implemented on the ground, such as forklift trucks and automated guided vehicles (AGVs).
- Overhead level: The overhead level is denoted for technologies that are implemented above the ground and do not consume space at floor level, e.g., overhead tow-line conveyor is classified as a floor level technology because it consumes not only overhead space but also floor-level space.

3.3.2 Working Network

The term *working network* is used for describing the potential flow paths of a specific technology class. Working networks are defined by tasks, a layout graph, technology specifications, building specifications, intra-workstation layout, …etc. The layout graph is defined as a two-dimensional graphical representation of the manufacturing facility. The layout graph is constituted by a finite set of nodes and a finite set of edges. The nodes denote the input and output points of workstations, intersections, and building column positions. The edges denote the potential aisle segments connecting adjacent input, output and intersection nodes. Figure 3-2(a) gives an example of a layout graph.

The rectangular boxes represent the intersections; the circles represent the input or/and output points of a workstation, and the diamonds represent the columns. An illustrative example of nine tasks is given in Figure 3-2(b). Each thick arrow depicts the origin (tail), and destination (head) of a task.

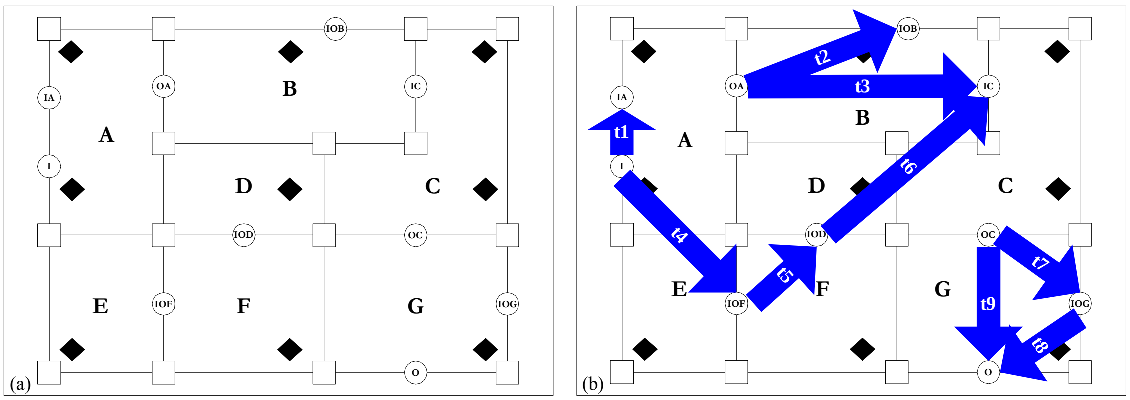

Figure 3-2: An Example of a Layout Graph and Tasks

Now, we are ready to introduce four major types of working networks, derived from the layout graph, for the transport technologies usually used in manufacturing.

(1) Aisle Network: The aisle network is mostly used by vehicle-based technologies, such as forklift trucks and automated guided vehicles. For each technology *e* that follows the aisle network, define a working network consisting of the following:

- The set of input and output nodes that are the origins and destinations of compatible tasks for technology *e* (I/O nodes);
- The set of nodes that are either intersection nodes or input and output nodes of incompatible tasks for technology *e* (Intersection nodes);
- A pair of arcs (i, j) and (j, i) are defined on each edge connecting node i and j in the layout graph, and
- The distance and technology-dependent flow capacity is defined on each arc.

Figure 3-3 gives the aisle network of the illustrative example, given that the tasks that are compatible with technology *e* are {*t*1, *t*4, *t*5, *t*6, *t*7, *t*9}. Note that the output point of workstation A, and input and output points of workstation B also belong to intersection nodes, represented as rectangular boxes in Figure 3-3(a); the compatible tasks of technology *e*, as shown in Figure 3-3(b), are not associated with them. From the perspective of technology *e*, only those nodes with pickup or delivery activities belong to I/O nodes, represented as circles in Figure 3-3(a) and (b).

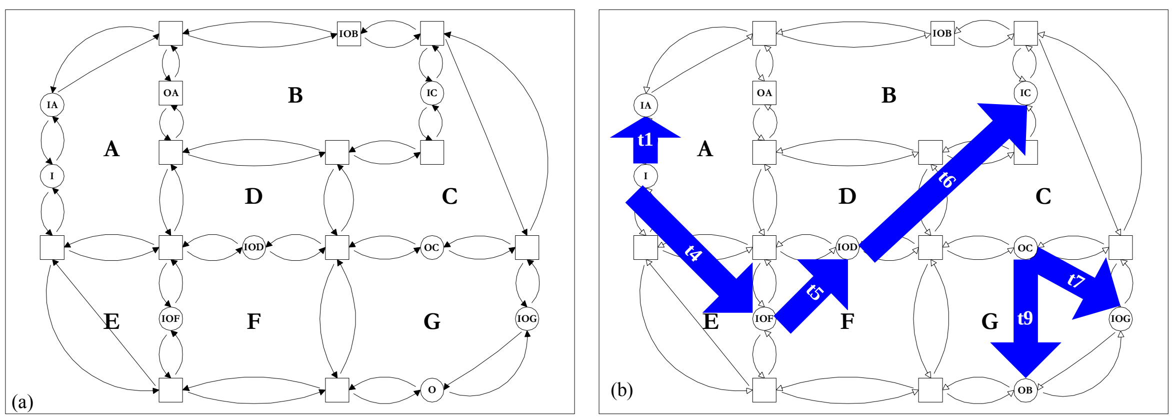

Figure 3-3: An Example of an Aisle Network: (a) Working Network, (b) Compatible Tasks

(2) Conveyor Network: Various types of floor-supported conveyors are the representative technologies that use a conveyor network. Floor-supported conveyors do not need to follow the contour of potential aisles. However, the intra-workstation layout might restrict their installation. Moreover, floor-supported conveyors conflict with other technologies, such as vehicle-based technologies, once they cross the potential aisles. For each technology *e* that follows the conveyor network, define a working network consisting of the following:

- The set of input and output nodes that are the origins and destinations of compatible tasks for technology *e* (I/O nodes);
- A pair of arcs (*i*, *j*) and (*j*, *i*) is induced from each edge connecting each pair of node *i* and *j* in I/O nodes, and
- The distance and technology-dependent flow capacity is defined on each arc.

Figure 3-4 gives the conveyor network of the illustrative example, given that the compatible tasks for technology *e* are {*t*2, *t*3, *t*7, *t*8, *t*9}. Note that the point-to-point line connection is just a logical representation. Figure 3-4(a) depicts the working network of technology *e*, and Figure 3-4(b) highlights the compatible tasks. Note that the conveyor network presented here does not take potential conflicts into consideration. To avoid undesirable conflicts with other technologies, a transformation is provided in CHAPTER 6 with application.

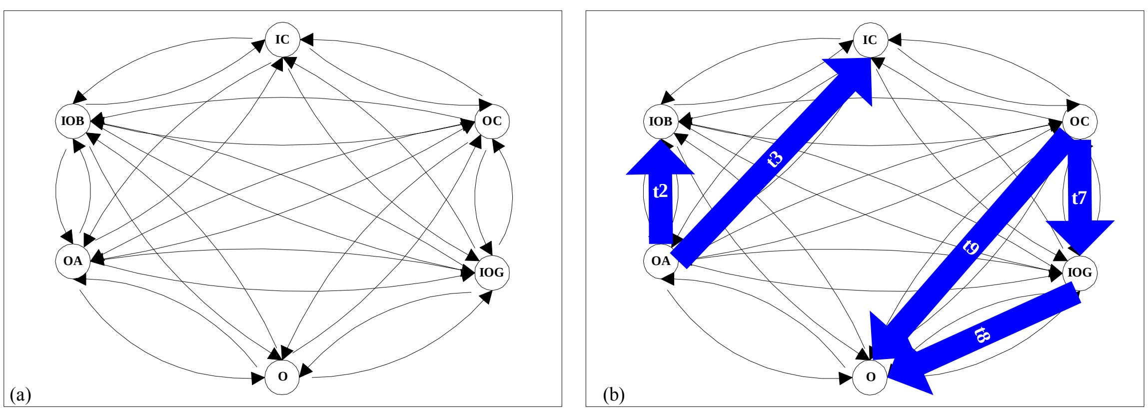

Figure 3-4: An Example of a Conveyor Network: (a) Working Network, (b) Compatible Tasks

(3) Overhead Network: The overhead network is dedicated to overhead conveyors. Their installation need not follow the contour of potential aisles, but the intra-workstation layout might restrict their installation. Furthermore, the installation of such technologies requires various types of vertical supports. Assume a set of edges that are suitable for the installation of overhead technology *e*. Note that the

graph formed by the input/output points and edge set is not necessarily simple. Multiple edges sharing the same endpoints are allowed.

For each technology *e* that follows the overhead network, define a working network consisting of following:

- The set of input and output nodes that are the origins and destinations of compatible tasks for technology *e* (I/O nodes);
- A pair of arcs (*i*, *j*) and (*j*, *i*) are defined on each edge connecting each pair of node *i* and *j* in the given edge set, and
- The distance and technology-dependent flow capacity is defined on each arc.

Figure 3-5 gives the overhead network of the illustrative example, given that the compatible tasks of overhead technology *e* are {*t*1, *t*2, *t*3, *t*5, *t*6}. Note that the point-to-point line connection is just a logical representation and the double arrows lines are used for clarity. Figure 3-5(a) depicts the working network, and Figure 3-5(b) highlights the compatible tasks of technology *e*.

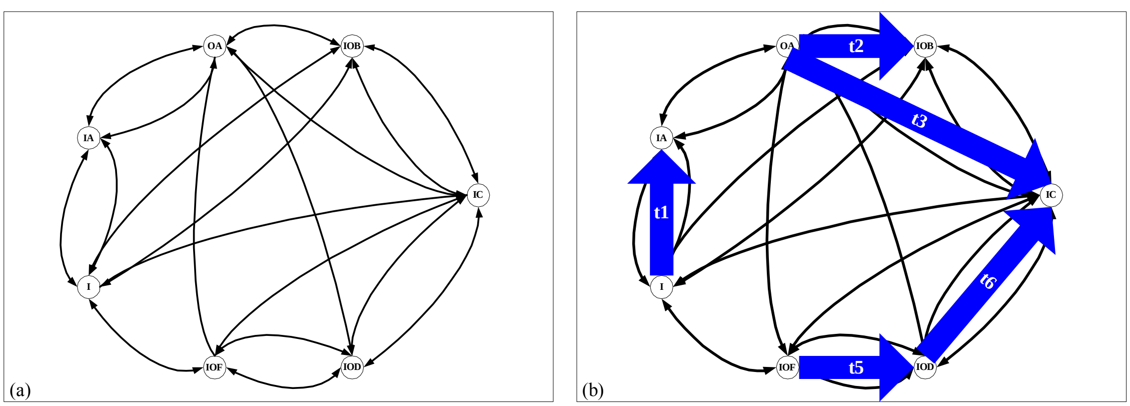

Figure 3-5: An Example of an Overhead Network: (a) Working Network, (b) Compatible Tasks

(4) Column Network: The column network is formed by connecting the columns of the facility with the result being a grid. The representative technology type that follows a column network is the bridge crane. The columns are used either as

supports for the tracks, or as restrictions on the movement of the hoist. For each technology *e* that follows the column network, define a working network consisting of the following:

- The set of input and output nodes that are the origins and destinations of compatible tasks for technology *e* (I/O nodes);
- The set of nodes that are column nodes in the layout graph, and
- A set of undirected orthogonal edges connecting pairs of columns.

Figure 3-6 gives the column network of the illustrative example, given that the compatible tasks are $\{t1, t7, t8\}$. Figure 3-6(a) depicts the working network and Figure 3-6(b) highlights the compatible tasks of technology *e*.

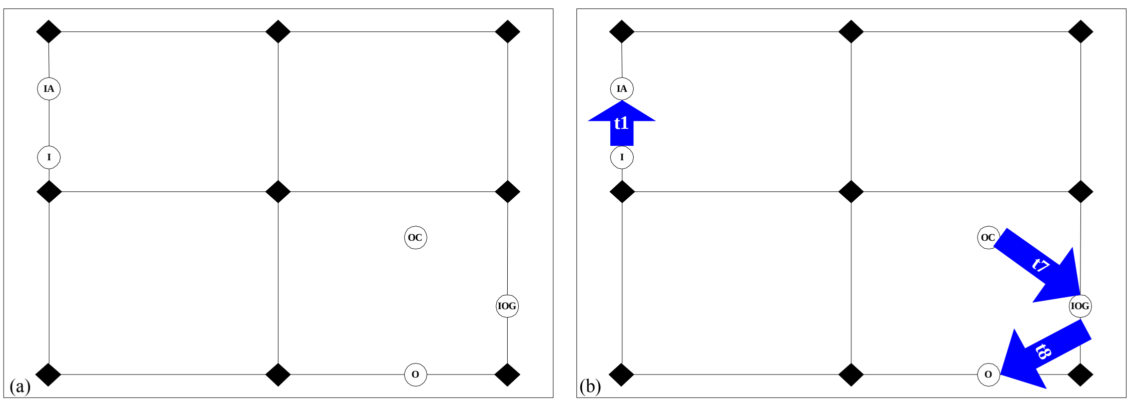

Figure 3-6: An Example of a Column Network: (a) Working Network, (b) Compatible Tasks

Note that the examples of working networks are just for illustrative purposes. Some modifications may be required for specific applications.

3.3.3 Empty Travel

Empty travel accounts for significant travel time in all technology classes except conveyor technologies. For ease of later reference, we call the technologies that require empty travel as carrier-based technologies.

3.3.4 *Network Restrictions*

Network restrictions are the constraints imposed on a technology to traverse its working network and service the designated tasks. There are three types of such restrictions:

- Connectivity: For a specific technology instance to serve its role the input and output points associated with origins and destinations of the designated tasks must be connected in a specific way on the resulting network. Here we introduce two specific connectivity requirements, I/O Strong Connectivity, and I/O Weak Connectivity, in the MTS design domain.
  - *I/O Strong Connectivity*: The associated input/output points must be connected in a subgraph induced from a working network such that there is a directed path from every origin point to any destination and from every destination point to any origin.
  - *I/O Weak Connectivity*: The associated input/output points must be connected in a subgraph induced from a working network such that there is a directed path from every origin to its destination.
- Capacity: On a working network of a technology, there is a capacity restriction imposed on each arc. For the bridge crane technology, there is a capacity restriction on each rectangle.
- Directionality: For some technology classes, there is a restriction on including both arcs that are induced from the same edge.

3.3.5 *Cost Structure*

The cost structure associated with the use of a tasks-resource combination consists of network connection costs and installation costs. The fixed cost of network connection is used to model the costs that are independent of flow intensity. The typical fixed costs considered in network connection are the cost of space consumption and cost of guide path. We refer to the fixed portion of network connection cost as *network construction cost*. The variable cost of network connection is used to model costs that vary with flow intensity and travel distance. The typical variable costs of network connection are the carrier requirements, direct labor, and power consumption. We refer to the cost proportional with the flow intensity as *network operating cost*.

For those cost elements that are not directly related to network construction and operating, it is not unusual for the costs, representing system design and control system, but no moving hardware, to exceed $100,000. Further, the moving hardware often can accommodate additional tasks with little increase in fixed costs and variable costs of network connection. We refer to this part of cost as *control system cost*. For the detailed cost modeling of each technology class, please refer to Appendix A.

3.3.6 Technology Classes and their Properties

According to the above criteria, we can categorize the transport technologies into six categories, as shown at Table 3-3. The technologies defined in category E^V are implemented at floor level along selected arcs of the aisle network. Due to the empty travel requirement, the arcs included must satisfy I/O strong connectivity. The flow on each included arc must respect the arc capacity. The technology subclass E^{VM} are mainly for manual-driven vehicle-based technologies. There is one more restriction on the technologies in the subclass E^{VA}: at most one of the arcs can be included for a pair of arcs that share the same endpoints. The representative technology in this class is the automated guided vehicle.

The technologies defined in class E^C are implemented on the floor level, and they traverse selected arcs of the conveyor network to serve the designated tasks. Since there is no requirement of empty travel, the associated origins and destinations of the designated tasks only need to be connected such that there is a directed path from every task origin to its destination. The flow on each included arc must respect the arc capacity. The representative technology in E^C is the roller conveyor.

Two subclasses E^{OT} and E^{OP} denote technologies that are implemented at the overhead level. Travel is along selected arcs of the overhead network to serve the designated tasks. The flow on each included arc must respect the arc capacity. These two subclasses, E^{OT} and E^{OP} are different in terms of their connectivity restrictions. For the technologies in E^{OP}, I/O strong connectivity must be kept. For the technologies defined in E^{OT}, the associated origins and destinations of the designated tasks must be in a closed trail since overhead trolleys are not allowed to split. The representative technology types for category E^{OP} are power-and-free conveyors and monorails, and the representative technology type for category E^{OT} is trolley conveyor.

The last technology class E^B is dedicated for overhead cranes. Cranes are installed at the overhead level of a building, and they serve the designated tasks within a restricted area. The associated origins and destinations of the designated tasks must be connected such that I/O strong connectivity is obtained. Moreover, these origins and destinations must be contained in a rectangle. Two parallel sides of this rectangle refer to the tracks used for supporting the crane. The capacity restriction is used for ensuring the technology can serve the transport requirements in a specific period of time. The representative technology in E^B is the bridge cranes.

Note that:

- For technology instances within the same class, their network characteristics are the same but different in terms of specifications, i.e., a counter-balanced forklift truck and a platform lift truck both belong to category E^{VM}. They share the same network characteristics, but they differ in terms of load sizes, speeds, etc.

- The classes are used for general classification of instances of transport technology. The applications are not unnecessarily restricted in this manner. For example, a designer may wish to evaluate a specific AGV used in a unidirectional network or in a bidirectional network. He only needs to specify another AGV with the same specifications in category E^{VM}, and adjust the affected characteristics, i.e., control cost, accordingly.
- The proposed classifications of transport technologies are intended to represent the majority of transport technology instances commonly used in manufacturing. There is no claim to be comprehensive.

Table 3-3: Technology Classes and their Properties

Technology class		Level	Working network	Empty travel	Network restrictions		
					Connectivity	Capacity	Directionality
Vehicle (**V**)	Automated (**A**)	Floor level	Aisle network	Yes	I/O Strong	Carriers	Yes
	Manual (**M**)	Floor level	Aisle network	Yes	I/O Strong	Carriers	No
Conveyor (**C**)		Floor level	Conveyor network	No	I/O Weak	Carriers	Yes
Overhead (**O**)	Trolley (**T**)	Overhead	Overhead network	Yes	Closed trail	Carriers	Yes
	P&F (**P**)	Overhead	Overhead network	Yes	I/O Strong	Carriers	Yes
Bridge crane (**B**)		Overhead	Column network	Yes	Rectangle within columns	Travel distance	No

3.4 Decisions and A Solution Framework of MTSDP

In CHAPTER 1, we briefly mentioned that the MTSDP consists of two classic design problems, the technology selection problem and the flow network design problem, in the planning of material transport system. In this section, we propose a decision framework of the MTSDP by presenting its decisions and the inter-relationships among these decisions.

If we see the MTSDP as an integrated problem, there are four major decisions involved:

(1) Compatibility of tasks and technologies,

(2) Task grouping,

(3) Flow network design, and

(4) Task group and technology assignment.

Compatibility of task and technology is introduced in Section 3.1. Task grouping means the aggregation of tasks into a task cluster. Note that a single task is allowed to be a task cluster. Flow network design is to provide a resulting network for a given technology and a given task cluster. Task group and technology assignment is to assign technologies to task clusters so that each task is serviced by one technology.

Except for decision (1), the other three decisions are clearly inter-related. Decision (1) provides the essential information for all three other decisions. Task groups provided by decision (2) are the input information for decisions (3) and (4). The flow network designs by decision (3) provide the cost information and space utilization for decision (4). Note that the cost information provided by flow network design could also be used for modifying the task clusters in decision (2). Last, task group and technology assignment could affect the decision (2) and (3) by considering the committed tasks and resources.

The required information and the inter-relationships of the four decisions of the MTSDP are provided in Figure 3-7. The dashed arrows indicate static information coming from outside of the MTSDP, and the solid arrows indicate the inter-relationship among decisions. Since the impact of compatibility of tasks and technologies is relatively straightforward, we treat decision (1) as another input of the MTSDP from this point on. Some methodologies in the literature (see Section 2.1 for details) can be applied to resolve the compatibilities of tasks and technologies. Note that each of the remaining decisions (shaded ovals in Figure 3-7) is not a simple problem. The focus of our research is to develop solution approaches for the intertwined decisions.

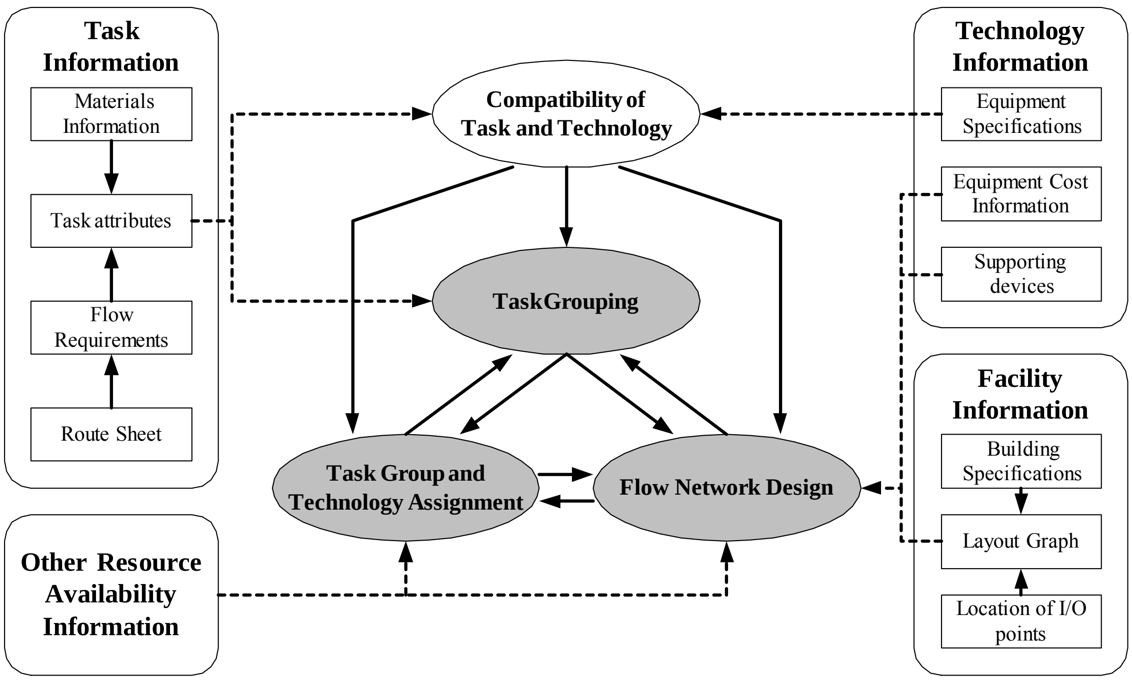

Figure 3-7: Decisions and Their Relationships of the MTSDP

CHAPTER 4

A COMPACT FORMULATION APPROACH TO THE MTSDP

In this chapter, we focus on compact formulations of the material transport system design problem (MTSDP). The objective of the MTSDP is to minimize the lifetime cost of the system, including network operating cost, network construction cost and control system cost. The cost model of each cost element will be introduced in Section 4.1. The constraints of MTSDP are discussed in Section 4.2. A Mixed Integer Nonlinear Programming (MINLP) formulation is presented in Section 4.3. Due to the difficulties of solving large nonlinear models, relaxation techniques are applied to linearize the nonlinear model. The resulting Mixed Integer Linear Programming (MILP) formulation can be solved by some powerful commercial solvers e.g., ILOG CPLEX, and it provides a lower bound to the optimal solution of the original problem. Although the compact MTSDP formulation can be solved by commercial solvers, the long solution time limits its applicability. To reduce solution time, we propose a tightening technique for the MILP formulation. The linear approximation and tightening technique for the MILP are discussed in Section 4.4. The effects of the tightened formulation and the impact of control system cost are illustrated by an example in Section 4.5. Section 4.6 concludes this chapter with some discussions.

4.1 Objective Function

The objective of this research is to provide a material transport system with minimum lifetime cost. The cost model, which accounts for the cost components of the entire life cycle of the system, can be divided into three major components: control system cost, network construction cost, and network operating cost.

4.1.1 Control System Cost

This cost component is used for modeling the control system cost of some technology types, e.g., AGVs, powered conveyor…etc. A fixed cost, C_e^{C1}, is incurred when the control device is purchased. The incremental cost, associated with the complexity of control system, is assumed to increase proportionally with the number of tasks serviced; it is modeled by cost element, C_e^{C2}. The control system cost is modeled as follows:

$$\sum_{e \in E}\left(\sum_{k \in T(e)}\left(C_e^{C1} x_{kke} + C_e^{C2} \sum_{t \in T(e)} x_{tke}\right)\right) \tag{4-1}$$

Note that the variable x_{kke} represents a seed variable to indicate if task *k* is chosen as the center of task-technology combination *ke*.

4.1.2 Network Construction Cost

The network construction cost relates to the fixed portion of material transport systems, e.g., frame structure for overhead technologies, guide path for AGV systems, or support and bed for floor conveyor technologies…etc. The network construction cost of arc (*i*, *j*) of technology *e* is denoted as C_{ije}^{f} and realized if arc (*i*, *j*) of technology *e* is included in the resulting design. Here the y_{ije} decision variable is a {0,1} variable indicating the selection of arc (*i*, *j*) of technology *e*. The detailed models of network construction costs for major technology classes are provided in Appendix A. Generally, the network construction cost is modeled as follows:

$$\sum_{e \in E} \sum_{(i,j) \in A(e)} C_{ije}^{f} y_{ije} \tag{4-2}$$

4.1.3 Network Operating Cost

The costs that are associated with network activity are modeled as network operating cost, e.g., purchase price per unit of technology, operating labor cost, power consumption, and maintenance cost. These are costs that vary proportionally with intensity of flow. The unit flow operating cost of arc (*i*, *j*) of technology *e* is modeled as C^{v}_{ije}; it increases with the sum of loaded flow and empty flow of technology *e* on arc (*i*, *j*). The continuous variable $\overline{f}_{ijtke}$ represents loaded flow of task *t* in tasktechnology combination *ke* on arc (*i*, *j*). Another continuous variable $\underline{f}_{ijtwke}$ represents empty flows between task t and w in tasktechnology combination *ke* on arc (*i*, *j*). The detailed models of network operating costs for the major technology classes are provided in Appendix A. In general, the network operation cost is modeled as follows:

$$\sum_{e\in E}\sum_{(i,j)\in A(e)} C^{v}_{ije}\left(\sum_{t\in T(e)}\sum_{k\in T(e)}\overline{f}_{ijtke}+\sum_{t\in T(e)}\sum_{w\in T(e)}\sum_{k\in T(e)}\underline{f}_{ijtwke}\right) \quad (4\text{-}3)$$

The cost model of MTSDP is provided in (4-4). The cost components on the right hand side of (4-4) denote the control system cost, network construction cost, and network operating cost, respectively. Note that cost elements should be properly amortized according to the planning horizon of each application.

$$\begin{aligned} Z_{MTSDP} = {} & \sum_{e\in E}\left(\sum_{k\in T(e)}\left(C^{C1}_{e}x_{kke}+C^{C2}_{e}\sum_{t\in T(e)}x_{tke}\right)\right)+ \\ & \sum_{e\in E}\sum_{(i,j)\in A(e)} C^{f}_{ije}y_{ije}+ \\ & \sum_{e\in E}\sum_{(i,j)\in A(e)} C^{v}_{ije}\left(\sum_{t\in T(e)}\sum_{k\in T(e)}\overline{f}_{ijtke}+\sum_{t\in T(e)}\sum_{w\in T(e)}\sum_{k\in T(e)}\underline{f}_{ijtwke}\right) \end{aligned}$$

(4-4)

4.2 Constraints

The minimum-cost objective of the MTSDP is restricted by constraints of transportation requests fulfillment, spatial restrictions of the facility, and topology constraints of technology classes. In addition, the technology flow on its working network must respect flow conservation and arc capacity constraints. Empty travel representation also imposes additional flow requirements on some nodes of the corresponding working networks. The rest of this subsection will provide detailed discussion on each constraint.

4.2.1 Membership Constraints

Membership constraints are used to ensure that the transportation requirements are satisfied. Each task must be assigned to exactly one task-technology combination. We employ variable x_{tke}, which equals 1 if task t is assigned to task-technology combination ke, and equals 0, otherwise. For every task t, constraint (4-5) ensures that the summation of all task-technology combinations must equal 1. The number of constraints (4-5) is the cardinality of set $T(e)$, $|T(e)|$, where $T(e)$ stands for the set of compatible tasks for technology e.

$$\sum_{e \in E} \sum_{k \in T(e)} x_{tke} = 1, \qquad \text{for any } t \in T(e)$$

(4-5)

Besides (4-5), we also need to make sure that task k is assigned to combination ke if there are other tasks assigned to combination ke. This can be ensured by constraints (4-6). The number of constraints (4-6) equals $\sum(|T(e)| \times |T(e)-1| : e \in E)$,

$$x_{tke} - x_{kke} \leq 0, \quad \text{for any } \{t, k \in T(e) : t \neq k\}, \text{for any } e \in E$$

(4-6)

4.2.2 Flow Balance Constraints for Loaded Travel

Flow balance constraints are used to ensure that the resulting loaded flow is conserved at every node. The loaded flow variable $\overline{f}_{ijtke}$ measures the amount of loaded flow of task *t*, cluster *k*, technology *e* on arc (*i*, *j*). On each node $i \in N(e)$ of the working network for technology *e*, the flow out minus flow in must equal to F_{te} ($-F_{te}$) if node *i* is the origin (destination) node of task *t* and task *t* is assigned to combination *ke*; otherwise, the flow out must equal the flow in. Constraints (4-7) ensure the conservation of loaded flow; the number of constraints is $\sum(|N(e)| \times |T(e)| \times |T(e)| : e \in E)$, where $N(e)$ and $A(e)$ stand for the node set and arc set of the working network of technology *e*, respectively, and $o(t)$ and $d(t)$ stand for the origin and destination of task *t*.

$$\sum_{j:(i,j)\in A(e)} \overline{f}_{ijtke} - \sum_{j:(j,i)\in A(e)} \overline{f}_{jitke} = \begin{cases} x_{tke}F_{te}, & \text{if } i = o(t) \\ -\ x_{tke}F_{te}, & \text{if } i = d(t), \\ 0, & \text{otherwise} \end{cases} \quad \begin{array}{c} \text{for any } i \in N(e), \text{for any } t \in T(e), \\ \text{for any } k \in T(e), \text{for any } e \in E \end{array}$$

(4-7)

4.2.3 Flow Balance Constraints for Empty Travel

As discussed in the literature review in Section 2.2.1, the impact of empty travel on a material transport system is threefold: operating time, network design, and carrier requirements. In this research, we adopt Kuhn's empty travel representation to model the empty travel of carrier-based technologies. Kuhn's representation assumes that the empty travel requirement at a task is a proportion of a task's loaded travel requirement.

Flow balance constraints here are used to ensure that the resulting empty flow is conserved at every node of the considered working network. If a cluster only consists of a single task, say task *t*, the empty travel is simply F_{te} units of supply at destination $d(t)$ and

F_{te} units of demand at origin $o(t)$. If cluster k consists of more than one task, say tasks t and w, the empty flows can be considered from a supply viewpoint as follows.

(1) F_{te} units of supply at destination $d(t)$, and $(\frac{F_{te}}{F_{te}+F_{we}}F_{te})$ of them must flow to $o(t)$ and $(\frac{F_{we}}{F_{te}+F_{we}}F_{te})$ of them must flow to $o(w)$,

(2) F_{we} units of supply at destination $d(w)$, and $(\frac{F_{te}}{F_{te}+F_{we}}F_{we})$ of them must flow to $o(t)$ and $(\frac{F_{we}}{F_{te}+F_{we}}F_{we})$ of them must flow to $o(w)$.

The empty flow variable, $\underline{f}_{ijtwke}$, is employed to measure the amount of empty flow of task t, task w, cluster k on arc (i, j) of technology e. To ensure the empty flow follows Kuhn's representation, we have flow balance constraints on two levels: aggregate level and detail level.

At the aggregate level, the empty flow balance constraints ensure that the flow in (flow out) of empty carriers equals the flow out (flow in) of loaded carriers over a pre-defined time period. At each node $i \in N(e)$ of the working network for technology e, the sum of flow out on all tasks w minus the sum of flow in on all tasks w must equal F_{te} ($-F_{te}$) if node i is the destination (origin) node of task t, and task t and w are assigned to combination ke; otherwise, the flow out must equal the flow in. Constraints (4-8) ensure the conservation of empty flow at the aggregate level; the number of constraints is $\sum(|N(e)|\times|T(e)|\times|T(e)|: e \in \{E^V \cup E^O\})$.

$$\sum_{w\in T(e)} \sum_{j:(i,j)\in A(e)} \underline{f}_{ijtwke} - \sum_{w\in T(e)} \sum_{j:(j,i)\in A(e)} \underline{f}_{jitwke} = \begin{cases} x_{tke}F_{te}, & \text{if } i = d(t) \\ -\ x_{tke}F_{te}, & \text{if } i = o(t), \\ 0, & \text{otherwise} \end{cases}$$

$$\text{for any } i \in N(e), \text{for any } k \in T(e), \text{for any } t \in T(e), \text{for any } e \in \{E^V \cup E^O\}$$

(4-8)

Although constraint (4-8) ensures the supply and demand of empty flow on related nodes, there is no guarantee that we will have empty flows according to Kuhn's representation. Therefore, we need to further specify the supply and demand of empty flow.

For technology *e* and cluster *k*, the total loaded flow is $\sum(x_{ske}F_{se} : s \in T(e))$. If tasks *t* and *w* are the same task, Kuhn's empty flow ratio can be obtained by $x_{tke}F_{te}$ divided by total loaded flow; otherwise, we need to make sure if tasks *t* and *w* are both in the same combination *ke*, and have empty flow ratio of $x_{tke}x_{wke}F_{we}$ divided by total loaded flow.

At this level of detail, the sum of flow out minus flow in must equal the product F_{te}($-F_{te}$) and Kuhn's ratio, if node *i* is the destination (origin) node of task *t* and task *t* is assigned to combination *ke*; otherwise, the flow out must be equal to flow in. Constraints (4-9-1) and (4-9-2) ensure the conservation of empty flow at the detailed level; the number of constraints is $\sum(|N(e)| \times |T(e)| \times |T(e)| \times |T(e)| : e \in E)$.

- If $t = w$

$$\sum_{j:(i,j)\in A(e)} f_{ijtwke} - \sum_{j:(j,i)\in A(e)} f_{jitwke} = \begin{cases} -\;F_{te}\left(\dfrac{F_{te}x_{tke}}{\sum(F_{se}x_{ske} : s \in T(e))}\right), & \text{if } i = o(t) \\ F_{te}\left(\dfrac{F_{te}x_{tke}}{\sum(F_{se}x_{ske} : s \in T(e))}\right), & \text{if } i = d(t) \\ 0, & \text{otherwise} \end{cases}$$

(4-9-1)

- If $t \neq w$

$$\sum_{j:(i,j)\in A(e)} \underline{f}_{ijtwke} - \sum_{j:(j,i)\in A(e)} \underline{f}_{jitwke} = \begin{cases} -\quad F_{te}\left(\dfrac{F_{te}x_{tke}x_{wke}}{\sum(F_{se}x_{ske} : s \in T(e))}\right), & \text{if } i = o(w) \\ \quad F_{te}\left(\dfrac{F_{te}x_{tke}x_{wke}}{\sum(F_{se}x_{ske} : s \in T(e))}\right), & \text{if } i = d(t) \\ \quad 0, & \text{otherwise} \end{cases}$$

$$\text{for any } i \in N(e), \text{for any } k \in T(e),$$
$$\text{for any } w \in T(e), \text{for any } t \in T(e), \text{for any } e \in \{E^V \cup E^O\} \qquad \text{(4-9-2)}$$

4.2.4 Arc Capacity Constraints

Arc capacity constraints are used to avoid congestion of flow on an arc. A fixed capacity is enforced once an arc of a working network is included, and the sum of loaded and empty flow on an arc cannot exceed the capacity. Constraint (4-10) not only ensures the capacity is respected, but also forces the arc inclusion if there is flow on it. U_{ije} is denoted as the arc capacity of technology *e* on arc (*i*, *j*). The number of constraints (4-10) is $\sum(|A(e)|: e \in E)$.

$$\sum_{t\in T(e)} \sum_{k\in T(e)} \overline{f}_{ijtke} + \sum_{t\in T(e)} \sum_{w\in T(e)} \sum_{k\in T(e)} \underline{f}_{ijtwke} \le U_{ije} y_{ije}, \qquad \text{for any } (i,\ j) \in A(e),$$
$$\text{for any } e \in E. \qquad \text{(4-10)}$$

4.2.5 Network Topology Constraints

Network topology constraints are used to model the physical network configuration of a technology. Two major topology requirements for commonly used transport technologies in manufacturing are introduced as follows:

- Directionality Constraints

Directionality constraints ensure that there is no bi-directional travel on an edge of the working network. Constraint (4-11) allows at most one of two opposite-directed arcs induced from the same edge to be included in the resulting network. The number of constraints is $\sum(|A(e)|: e \in \{E^{VA} \cup E^{C} \cup E^{OP} \cup E^{OT}\})$.

$$y_{ije} + y_{jie} \leq 1, \qquad \text{for any } (i, j) \in A(e), \text{ where } e \in \{E^{VA} \cup E^{C} \cup E^{OP} \cup E^{OT}\} \tag{4-11}$$

- Degree Zero Constraints

Degree zero constraints ensure that the out degree equals the in degree of a node. Constraint (4-12) forces the number of tails (of arcs) to be equal to the number of heads (of arcs) incident at a node. The number of constraints (4-12) is $|A(e)|$, where $e \in E^{OT}$.

$$\sum_{j:(i,j)\in A(e)} y_{ije} - \sum_{j:(j,i)\in A(e)} y_{jie} = 0, \qquad \text{for any } (i, j) \in A(e), \text{ where } e \in E^{OT}. \tag{4-12}$$

4.3 Compact MINLP Formulation

Based on the objective function and constraints provided in Sections 4.1 and 4.2, an compact formulation is presented in Section 4.3.1. The validity of the proposed formulation is investigated in Section 4.3.2, and the size of the proposed formulation is analyzed in Section 4.3.3.

4.3.1 Formulation

The proposed compact model is formulated as a mixed integer nonlinear program as shown in Figure 4-1. This formulation is to minimize the lifetime cost of the material transport system as shown in (4-4) subject to constraints (4-5) to (4-12). Note that the constraints (4-9-1) and (4-9-2) that ensure that the empty travel follows Kuhn's presentation are not linear because of the presence of divisions of linear functions

$\left(\frac{F_{te}x_{tke}}{\sum\left(F_{se}x_{ske}:s\in T(e)\right)}\right)$ and $\left(\frac{F_{we}x_{tke}x_{wke}}{\sum\left(F_{se}x_{ske}:s\in T(e)\right)}\right)$. Also note that this formulation is just for illustrative purpose. The denominator might be undefined in constraints (4-9-1) and (4-9-2) if none of the tasks is assigned to task-technology combination *ke*.

4.3.2 Validity of the Proposed Formulation

This section addresses the *validity* of the proposed formulation for the MTSDP. Note that feasible solutions of a valid formulation must be feasible solutions of the original problem. In other words, we need to show that a solution that satisfies constraints (4-5) ~ (4-12) is a feasible solution of the material transport design. As discussed earlier, a feasible material transport system design must satisfy the following requirements:

Requirement 1: Each task must be handled by exactly one technology.

Requirement 2: Transport demand is satisfied by loaded travel.

Requirement 3: Empty travel follows Kuhn's representation.

Requirement 4: Spatial restrictions of the facility are satisfied.

Requirement 5: Arc capacity of flow is respected.

Requirement 6: Network restrictions for each technology class are satisfied.

It is straightforward to see that the proposed formulation satisfies Requirement 1, 2, 4, and 5. Constraints (4-5) and (4-6) satisfy Requirement 1 by requiring that each task be serviced by exactly one task-resource combination. Requirement 2 is ensured by constraints (4-7). Requirement 4 is satisfied by the ways to prepare the working networks, and Requirement 5 is satisfied by constraints (4-10).

$$\text{Minimize } Z_{\text{MTSDP}} = \sum_{e\in E}\sum_{k\in T(e)}\left(C_e^{C1}x_{kke} + \sum_{t\in T(e)} C_e^{C2}x_{tke}\right) + \sum_{e\in E}\sum_{(i,j)\in A(e)} C_{ije}^{f} y_{ije} + \sum_{e\in E}\sum_{(i,j)\in A(e)} C_{ije}^{v}\left(\sum_{t\in T(e)}\sum_{k\in T(e)} \overline{f}_{ijtke} + \sum_{t\in T(e)}\sum_{w\in T(e)}\sum_{k\in T(e)} \underline{f}_{ijtwke}\right)$$

Subject to

$$\sum_{e\in E}\sum_{k\in T(e)} x_{tke} = 1, \quad \text{for any } t\in T(e)$$

$$x_{tke} - x_{kke} \le 0, \quad \text{for any } \{t,k\in T(e):\ t\ne k\}, \text{ for any } e\in E$$

$$\sum_{j:(i,j)\in A(e)} \overline{f}_{ijtke} - \sum_{j:(j,i)\in A(e)} \overline{f}_{jitke} = \begin{cases} F_{te}x_{tke}, & \text{if } i=o(t) \\ -\ F_{te}x_{tke}, & \text{if } i=d(t), \\ 0, & \text{otherwise} \end{cases} \quad \begin{matrix}\text{for any } i\in N(e), \text{ for any } k\in T(e), \\ \text{for any } t\in T(e), \text{ for any } e\in E\end{matrix}$$

$$\sum_{w\in T(e)}\sum_{j:(i,j)\in A(e)} \underline{f}_{ijtwke} - \sum_{w\in T(e)}\sum_{j:(j,i)\in A(e)} \underline{f}_{jitwke} = \begin{cases} x_{tke}F_{te}, & \text{if } i=d(t) \\ -\ x_{tke}F_{te}, & \text{if } i=o(t), \\ 0, & \text{otherwise} \end{cases} \quad \begin{matrix}\text{for any } i\in N(e), \text{ for any } k\in T, \\ \text{for any } t\in T, \text{ for any } e\in \{E^{V}\cup E^{O}\}\end{matrix}$$

$$\sum_{j:(i,j)\in A(e)} \underline{f}_{ijtwke} - \sum_{j:(j,i)\in A(e)} \underline{f}_{jitwke} = \begin{cases} -\ F_{te}\left(\dfrac{F_{te}x_{tke}}{\sum(F_{se}x_{ske} : s\in T)}\right), & \text{if } i=o(t) \\ F_{te}\left(\dfrac{F_{te}x_{tke}}{\sum(F_{se}x_{ske} : s\in T)}\right), & \text{if } i=d(t), \quad \text{if } t=w \\ 0, & \text{otherwise} \end{cases}$$

for any $i\in N(e)$, for any $k\in T(e)$, for any $w\in T(e)$, for any $t\in T(e)$, for any $e\in\{E^{V}\cup E^{O}\}$

$$\sum_{j:(i,j)\in A(e)} \underline{f}_{ijtwke} - \sum_{j:(j,i)\in A(e)} \underline{f}_{jitwke} = \begin{cases} -\ F_{te}\left(\dfrac{F_{te}x_{tke}x_{wke}}{\sum(F_{se}x_{ske} : s\in T)}\right), & \text{if } i=o(w) \\ F_{te}\left(\dfrac{F_{te}x_{tke}x_{wke}}{\sum(F_{se}x_{ske} : s\in T)}\right), & \text{if } i=d(t) \quad \text{if } t\ne w \\ 0, & \text{otherwise} \end{cases}$$

for any $i\in N(e)$, for any $k\in T(e)$, for any $w\in T(e)$, for any $t\in T(e)$, for any $e\in\{E^{V}\cup E^{O}\}$

$$\sum_{t\in T(e)}\sum_{k\in T(e)} \overline{f}_{ijtke} + \sum_{t\in T(e)}\sum_{w\in T(e)}\sum_{k\in T(e)} \underline{f}_{ijtwke} \le U_{ije}y_{ije}, \quad \text{for any } (i,j)\in A(e),\ \text{for any } e\in\{E^{AV}\cup E^{C}\cup E^{O}\}$$

$$y_{ije} + y_{jie} = 1, \quad \text{for any } (i,j)\in A(e), \text{ for any } e\in\{E^{AV}\cup E^{C}\cup E^{O}\}$$

$$\sum_{(i,j)\in A(e)} y_{ije} + \sum_{(j,i)\in A(e)} y_{jie} = 0, \quad \text{for any } (i,j)\in A(e), \text{ for any } e\in E^{OT}$$

$$x_{tke}\in\{0,1\}, \quad \text{for any } t\in T(e), \text{ for any } k\in T(e), \text{ for any } e\in E$$

$$y_{ije}\in\{0,1\}, \quad \text{for any } (i,j)\in A(e), \text{ for any } e\in E$$

$$\overline{f}_{ijtke}\ge 0, \quad \text{for any } (i,j)\in A(e), \text{ for any } t\in T(e), \text{ for any } k\in T(e), \text{ for any } e\in E$$

$$\underline{f}_{ijtwke}\ge 0, \quad \text{for any } (i,j)\in A(e), \text{ for any } t\in T(e), \text{ for any } w\in T(e), \text{ for any } k\in T(e), \text{ for any } e\in E$$

Figure 4-1: MINLP Formulation of the MTSDP

Requirement 3 concerns empty travel within a technology-tasks combination (or sub-system). As addressed earlier, tasks are grouped following constraints (4-5) and (4-6). Constraints (4-7) reflect the given transport requirements. Constraints (4-8), (4-9-1), and (4-9-2) ensure that the empty flow follows Kuhn's empty travel representation for each task cluster.

Recall the network restrictions introduced in Section 3.3.4: *I/O strong connectivity* requires a directed path from every origin to any destination and from every destination to any origin. Given a tasks cluster $T^{'}$ and a technology, constraints (4-7) and (4-10) ensure that there is a directed path from the origin to the destination of any task in $T^{'}$. Moreover, constraints (4-8), (4-9-1), (4-9-2) and (4-10) ensure that there is a directed path from the destination of any task in $T^{'}$ to the origin of all tasks in $T^{'}$. Therefore, there must be a directed path from every destination to any origin of tasks in $T^{'}$. This argument results in an observation:

Observation 1. Constraints (4-7), (4-8), (4-9-1), (4-9-2), and (4-10) guarantee I/O Strong Connectivity.

Another connectivity requirement introduced in Section 2.4.4 is *closed trail*. Closed trail is a directed cycle with node repetitions allowed and, thus, a less-restricted case of the well-known Hamiltonian Cycle Problem. Appling the same argument used in Observation 1, constraints (4-7), (4-8), (4-9-1), (4-9-2) and (4-10) guarantee the I/O strong connectivity and sub-tour free sub-graph. However, a sub-graph with imbalance of node degree cannot be excluded by these constraints. Therefore, constraints (4-11) are brought in to prevent a bi-directional network and constraints (4-12) are used to maintain a degree-balanced network. This argument leads to the observation:

Observation 2. Constraints (4-7), (4-8), (4-9-1), (4-9-2), (4-10), (4-11), and (4-12) guarantee a closed trail.

Requirement 6 concerns the network restrictions of each technology class (for details, see Section 2.4.4). For technology class E^{VM} (manually driven vehicle), which allows bi-directional travel, constraints (4-7), (4-8), (4-9-1), (4-9-2), and (4-10) ensure I/O strong connectivity and capacity restrictions. For technology class E^{C} (floor-supported conveyor), which has no empty travel, constraints (4-7) and (4-10) ensure the connectivity and capacity restrictions. For technology classes E^{VA} and E^{OP} (automated guided vehicle and overhead power-and-free conveyor), constraints (4-7), (4-8), (4-9-1), (4-9-2), (4-10), and (4-11) ensure the I/O strong connectivity, directionality, and capacity restrictions. For technology class E^{OT} (overhead trolley conveyor), constraints (4-7), (4-8), (4-9-1), (4-9-2), (4-10), (4-11) and (4-12) ensure the closed trail connectivity, directionality, and capacity restrictions.

4.3.3 Size of the MINLP Formulation

If a MTS design problem has $|T|$ tasks, $|E|$ candidate technologies and the working network of each technology has $|N|$ nodes, the total number of constraints of the proposed MINLP formulation are $|E|(|T|^2-|T|+|N|(3|T|^2+|T|^3+|N|))+|T|$, and the total number of variables are $|E|(|T|^2+|N|^2(1+|T|^2+|T|^3))$, where $|E|(|T|^2+|N|^2)$ of them are binary variables.

Note that these numbers only serve as upper bounds of actual problem size. The exact sizes of problems depend upon the compatibility of tasks and technologies, and the sparseness of the working networks. A MTS design problem with 9 tasks, 4 candidate technologies, and 25 nodes on each working network of technology yields an upper bound of approximately 99×10^3 constraints, and 2×10^6 variables, where 2.8×10^3 of them are binary variables.

4.4 Relaxations of the MINLP Formulation

This section addresses relaxations of the compact formulation proposed in Section 4.3. The proposed formulation is not only large in terms of size, but also nonlinear in some constraints, which prevents us from taking advantage of powerful commercial solvers. Therefore, we apply some linear relaxation techniques from the literature to approximate constraints (4-9-1) and (4-9-2). Section 4.4.1 and 4.4.2 introduces these linear approximations, respectively. Section 4.4.3 discusses the solution quality of this relaxed formulation. A tighter formulation in terms of LP relaxation is proposed in Section 4.4.4. Section 4.4.5 summaries the extra number of variables and constraints required by the linear relaxations.

4.4.1 Relaxation of Constraint (4-9-1)

As described in Sections 4.2.3 and 4.3.1, constraints (4-9-1) and (4-9-2) are nonlinear for Kuhn's empty travel representation. Constraint (4-9-1) models empty flow where task *t* and task *w* are the same task. Let the numerator $F_{te}x_{tke} = \overline{g}_{itwke}$ and the denominator $\sum\left(F_{se}x_{ske} : s \in T(e)\right) = \underline{g}_{itwke}$. Kuhn's empty travel ratio, $g_{itwke} = \overline{g}_{itwke} \big/ \underline{g}_{itwke}$, results in a product of linear functions.

Denote $L_{\overline{g}}, U_{\overline{g}}, L_{\underline{g}}, U_{\underline{g}}, L_g$, and U_g as the lower and upper bounds of $\overline{g}_{itwke}$, $\underline{g}_{itwke}$, and g_{itwke} respectively. Recall that x_{tke} is binary integer variable. The numerator is bounded by $L_{\overline{g}} = 0 \le \overline{g}_{itwke} \le F_{te} = U_{\overline{g}}$, the denominator is bounded by $L_{\underline{g}} = 0 \le \underline{g}_{itwke} \le \sum\left(F_{se} : s \in T(e)\right) = U_{\underline{g}}$, and the ratio of empty flow is bounded as $L_g = 0 \le g_{itwke} \le 1 = U_g$. Constraint (4-9-1) can be re-written as follows:

$$\sum_{j:(i,j)\in A(e)} \underline{f}_{ijtwke} - \sum_{j:(j,i)\in A(e)} \underline{f}_{jitwke} = \begin{cases} -\ F_{te} g_{itwke}, & \text{if } i = o(t) \\ F_{te} g_{itwke}, & \text{if } i = d(t) \\ 0, & \text{if } i \neq o(t) \text{ and } i \neq d(t) \end{cases}$$

for any $i \in N(e)$, for any $k \in T(e)$, for any $w \in T(e)$, for any $t \in T(e)$, for any $e \in \{E^V \cup E^O\}$

(4-9-1a)

According to a recent work, Hwang and Al-Khayyal (2004), the ratio of empty flow, a product of linear functions, can be approximated by a set of linear inequalities. Following the variables used in this research, these inequalities are summarized in Table 4-1. Inequalities (1), (2), (3) and (4) are used for specifying the lower and upper bounds of $\overline{g}_{itwke}$, $\underline{g}_{itwke}$, and g_{itwke}. Inequalities (5), (6) and (7) are used for setting the relationships between the numerator and the denominator of the empty flow ratio.

Table 4-1: Linear Inequalities of the Approximation on Kuhn's Empty Travel Ratio

(1)	$\overline{g}_{itwke} \leq F_{te}$
(2)	$0 \leq g_{itwke} \leq 1$
(3)	$0 \leq \underline{g}_{itwke} \leq \sum(F_{se} : s \in T(e))$
(4)	$\overline{g}_{itwke} \geq 0$
(5)	$\overline{g}_{itwke} \geq g_{itwke}(\sum(F_{se} : s \in T(e))) + \underline{g}_{itwke} - \sum(F_{se} : s \in T(e))$
(6)	$\overline{g}_{itwke} \leq g_{itwke}(\sum(F_{se} : s \in T(e)))$
(7)	$\overline{g}_{itwke} \leq \underline{g}_{itwke}$

Applying linear approximations on the compact formulation, nonlinear constraint (4-9-1) can be approximated by linear constraints (4-9-1a) ~ (4-9-1i) and three more positive continuous variables.

$$\overline{g}_{itwke} = F_{te} x_{tke} \tag{4-9-1b}$$

$$\underline{g}_{itwke} = \sum(F_{se} x_{ske} : s \in T(e)) \tag{4-9-1c}$$

$$0 \leq \overline{g}_{itwke} \leq F_{te} \tag{4-9-1d}$$

$$0 \leq g_{itwke} \leq 1 \tag{4-9-1e}$$

$$0 \le \underline{g}_{itwke} \le \sum\left(F_{se} : s \in T(e)\right) \tag{4-9-1f}$$

$$\overline{g}_{itwke} \ge g_{itwke}\left(\sum\left(F_{se} : s \in T(e)\right)\right) + \underline{g}_{itwke} - \sum\left(F_{se} : s \in T(e)\right) \tag{4-9-1g}$$

$$\overline{g}_{itwke} \le g_{itwke}\left(\sum\left(F_{se} : s \in T(e)\right)\right) \tag{4-9-1h}$$

$$\overline{g}_{itwke} \le \underline{g}_{itwke} \tag{4-9-1i}$$

4.4.2 Relaxation of Constraint (4-9-2)

Constraint (4-9-2) models empty flows between task *t* and another task *w*. For a pair of tasks to be connected by empty flows, they must be assigned to the same transport technology and grouped in the same task cluster. In other words, the empty flow between task *t* and another task *w* will be triggered only if their clustering variables x_{tke} and x_{wke} are equal to 1 for the same task-technology combination ke.

On the right hand side of constraint (4-9-2), there are quadratic terms $x_{tke}x_{wke}$ in the numerator of the empty flow ratio. Since the clustering variables are 0-1 variables, we can obtain an equivalent linear description, see Plastria (2002) for details, by introducing a new variable $\hat{g}_{twke}$, where $\hat{g}_{twke} \in \{0,1\}$ and three constraints (4-9-2j), (4-9-2k), and (4-9-2w).

$$-x_{tke} + \hat{g}_{twke} \le 0 \tag{4-9-2j}$$

$$-x_{wke} + \hat{g}_{twke} \le 0 \tag{4-9-2k}$$

$$x_{tke} + x_{wke} - \hat{g}_{twke} \le 1 \tag{4-9-2w}$$

Let the numerator $F_{te}\hat{g}_{twke} = \overline{g}_{itwke}$ and the denominator $\sum\left(F_{se}x_{ske} : s \in T(e)\right) = \underline{g}_{itwke}$. The ratio of the empty flow approximation, $g_{itwke} = \overline{g}_{itwke} \big/ \underline{g}_{itwke}$, results in a product of linear functions. By performing a similar linear approximation as introduced in Section 4.4.1, nonlinear constraints (4-9-2) can be approximated by linear constraints (4-9-2a) ~

(4-9-2w). Notice that in (4-9-2b) $\overline{g}_{itwke} = F_{te}\hat{g}_{wtke}$ and constraints (4-9-2c) ~ (4-9-2i) are identical with (4-9-1c) ~ (4-9-1i).

4.4.3 About the Linear Approximation of MINLP Formulation

In sections 4.4.1 and 4.4.2, we apply linear approximation techniques from the literature to make the compact formulation a linear model. The linearization of quadratic 0-1 variables introduced in Section 4.4.2 is an equivalent description. However, the linearization of the empty flow ratio introduced in Section 4.4.1 is an approximation to the original formulation. To illustrate the approximation of the empty flow ratio, let us revisit constraints (4-9-1g), (4-9-1h), and (4-9-1i).

Constraint (4-9-1i) forces the denominator of the empty flow ratio to be greater than or equal to the numerator. Its implication in this application is that the sum of total empty flow of a specific technology-task cluster combination must be greater than or equal to the empty flow of any single task within the cluster.

To illustrate the implications of (4-9-1g) and (4-9-1h), we view these two inequalities from the perspective of the empty flow ratio, g_{itwke}. Constraints (4-9-1h) enforce $g_{itwke} \geq \overline{g}_{itwke} / \left(\sum\left(F_{se} : s \in T(e)\right)\right)$. Compared to the original denominator of the empty flow ratio, constraints (4-9-1h) assume that every task is included in a specific technology-task cluster combination ($x_{ske} = 1,\ \forall s \in T(e)$). Therefore, the ratio that satisfies constraint (4-9-1h) provides a lower bound of the true empty flow ratio.

Constraints (4-9-1g) ensure that the empty travel ratio by Kuhn's representation $g_{itwke} \leq (\overline{g}_{itwke} / (\sum(F_{se} : s \in T(e)))) - (\underline{g}_{itwke} / (\sum(F_{se} : s \in T(e)))) + 1$. According to constraints (4-9-1f) and (4-9-1i), $\underline{g}_{itwke}$ is lower and upper bounded by $\overline{g}_{itwke}$ and $(\sum(F_{se} : s \in T(e)))$. Taking the boundary conditions of $\underline{g}_{itwke}$ as extreme conditions for the empty flow ratio, we can get $g_{itwke} \le 1$ if $\underline{g}_{itwke} = \bar{g}_{itwke}$, and $g_{itwke} \le \bar{g}_{itwke} \big/ \underline{g}_{itwke}$ if $\underline{g}_{itwke} = (\sum (F_{se} : s \in T(e)))$. In other words, the empty flow ratio that satisfies constraint (4-9-1g) will be somewhere between $\bar{g}_{itwke} \big/ \underline{g}_{itwke}$ and 1. Therefore, constraint (4-9-1g) provides an upper bound of the true empty flow ratio.

In essence, the linear approximation technique introduced in section 4.4.1 replaces the nonlinear empty travel ratio by a set of linear inequalities. The equalities of constraints (4-9-1) and (4-9-2) are relaxed by a pair of lower/upper bounding inequalities. In terms of the compact formulation, this approximation provides the true empty flow ratio only when $\underline{g}_{itwke} = (\sum (F_{se} : s \in T(e)))$, that is, all tasks are included in a specific technology-task cluster. Since our objective function is to minimize cost, the solutions of this approximation will lead to a minimum cost solution within the bounds provided by constraints (4-9-1g), (4-9-1h), and (4-9-1i). In general, the objective value with this linear relaxation will be an underestimate of the original MINLP formulation since the empty flow ratio does not exactly follow Kuhn's empty travel representation.

From the perspective of solutions, the linear approximation still maintains the network topology requirements since there is empty flow out at a destination node and empty flow in at an origin node if the task is included in the technology-task cluster. Therefore, observations 1 and 2 still hold in this linear formulation. However, the task clusters and network designs might be different from those obtained by solving the problem with exact empty flow ratios.

4.4.4 Tightening Constraints

In the integrated formulation, constraints (4-10) ensure that the arc of a working network *e* is included in the resulting design if there is flow on arc (*i*, *j*), and the sum of all flows on an arc (i, j) does not exceeds its capacity, U_{ije}. Let **P** = {Constraints (4-10) and $\overline{f}_{ijtke} \geq 0$, $\underline{f}_{ijtwke} \geq 0$, $0 \leq y_{ije} \leq 1$}, and $\mathbf{P_a}$ = {Constraints (4-10a) and $\overline{f}_{ijtke} \geq 0$, $\underline{f}_{ijtwke} \geq 0$, $0 \leq y_{ije} \leq 1$}.

- (Constraint (4-10))

$$\sum_{t \in T} \sum_{k \in T} \overline{f}_{ijtke} + \sum_{t \in T} \sum_{w \in T} \sum_{k \in T} \underline{f}_{ijtwke} \leq U_{ije} y_{ije},$$
$$\text{for any } (i, j) \in A(e), \text{for any } e \in E.$$

- (Constraint (4-10a))

$$\sum_{t \in T} \sum_{k \in T} \overline{f}_{ijtke} + \sum_{t \in T} \sum_{w \in T} \sum_{k \in T} \underline{f}_{ijtwke} \leq \text{Min}(U_{ije}, 2D_e) y_{ije}, \text{ where } D_e = \sum (F_{te} : t \in T(e))$$
$$\text{for any } (i, j) \in A(e), \text{for any } e \in E.$$

Observation 3. $\mathbf{P_a}$ is stronger than P

First of all, we need to show that both **P** and $\mathbf{P_a}$ are valid formulation for MTSDP. The validity of constraint (4-10) is shown in Section 4.3.2. The difference of constraints (4-10) and (4-10a) is the treatment of arc capacity. Regardless of the arc capacity, the heaviest possible flow of loaded and empty travel on arc (i, j) for a working network of technology e is the sum of flows of the tasks that can be handled by technology e, represented by D_e. This value can be used to bound the arc flows. The sum of empty flows of tasks in the cluster cannot exceed D_e, so the value $2D_e$ enters the right hand side of constraints (4-10a). Thus, constraint (4-10a) is also a valid formulation for MTSDP.

Secondly, we need to show that any feasible solution $(\overline{\mathrm{f}}, \underline{\mathrm{f}}, \mathrm{y})$ for $\mathbf{P_a}$ is also a feasible solution for **P**. If $U_{ije} \geq 2D_e$, $\mathbf{P_a}$ and **P** are the same. Any feasible solution for $\mathbf{P_a}$ is also a feasible solution for **P**. On the other hand, if $U_{ije} < 2D_e$, since the sum of loaded and empty travel is at most $2D_e$, any feasible solution for $\mathbf{P_a}$ is also a feasible solution for **P**.

As for the strong part, we will show it by an example that is feasible in **P** but not in $\mathbf{P_a}$. Without losing generality, let two tasks, t_1 and t_2, have demand F_{1e}=1 and F_{2e}=1, respectively. The capacity on arc (i, j) of the working network for technology e is U_{ije}= 5. **P** and $\mathbf{P_a}$ can be written as follows:

$$
\begin{aligned}
\text{(P)}\quad & \overline{f}_{11ije} + \overline{f}_{12ije} + \overline{f}_{21ije} + \overline{f}_{22ije} + \\
& \underline{f}_{111ije} + \underline{f}_{112ije} + \underline{f}_{121ije} + \underline{f}_{122ije} + \\
& \underline{f}_{211ije} + \underline{f}_{212ije} + \underline{f}_{221ije} + \underline{f}_{222ije} \le 5y_{ije}
\end{aligned}
$$

$$
\begin{aligned}
(\text{P}_\text{a})\quad & \overline{f}_{11ije} + \overline{f}_{12ije} + \overline{f}_{21ije} + \overline{f}_{22ije} + \\
& \underline{f}_{111ije} + \underline{f}_{112ije} + \underline{f}_{121ije} + \underline{f}_{122ije} + \\
& \underline{f}_{211ije} + \underline{f}_{212ije} + \underline{f}_{221ije} + \underline{f}_{222ije} \le 4y_{ije}
\end{aligned}
$$

Consider a solution (1,0,0,1,1,0,0,0,0,0,0,1,1/5) that is feasible in **P** but not feasible in $\mathbf{P_a}$. Therefore, formulation $\mathbf{P_a}$ is stronger than **P**.

4.4.5 Size of MILP Formulation of MTSDP

The size of the original nonlinear formulation is given in Section 4.3.3. In order to make the proposed formulation a linear model, we need to add more variables and constraints. If a MTS design problem has $|T|$ tasks, $|E|$ candidate technologies and the working network of each technology has $|N|$ nodes, $|T|^3|E|(1+3|N|)$ extra continuous variables and $2|E||T|^2(11|T|-3))$ more constraints are needed for the linear approximation. A MTS design problem with 9 tasks, 4 candidate technologies, and 25 nodes on each working network of technology yields an upper bound of approximately 162×10^3 constraints, and 2×10^6 variables, where 5.74×10^3 of them are binary variables. The increases in numbers are 62.2%, 10.9%, and 103.3% over the MINLP formulation.

4.5 Computational Experiments

In this section, we demonstrate the performances of the proposed formulations and mathematical models of the MTSDP (CF approach in short). The first experiment is to validate the tight constraint proposed in Section 4.4. A comparison of the MILP formulation (original formulation in short) and the MILP formulation with tight capacity constraint (tight formulation in short) is presented by an example. The second experiment is to demonstrate task clustering with different control cost scenarios.

In this example, there are nine tasks with origins and destinations shown in Figure 4-2, e.g., task 1 originates at the facility inbound point and ends at the input point of workstation A. For these nine tasks, we consider four technologies to serve their needs: technology one, denoted e1, is counter-balance lift truck; technology two, e2, is unit-load AGV; technology three, e3, is overhead power-and-free conveyor; technology four, e4, is overhead trolley conveyor. The compatibility of tasks and technologies, and the hourly demands of tasks (in unit loads) are given in Table 4-2, e.g., the absence of an entry for t2 and e1 means that technology one is incapable of handling task 2. The entry for t1 and e1 indicates that there are 60 unit loads of e1 per hour, if task one is handled by technology one.

The speed, hourly network operating cost, and network construction cost of flow network design of four example technologies are summarized in Table 4-3. The network operating cost includes carrier purchase, driver wage, power, and maintenance cost; the network construction cost includes guide path/support, space, maintenance and connection. The cost structure varies with the technology; both network operating cost and network construction cost are amortized over five years, assuming that the factory operates 300 days per year and 7 hours per day.

The computational experiments presented in this section were performed on a Sun workstation 220R with 2*360MHz UltraSparc II CPU's and 2GB RAM. We solved all optimization models of MTSDP by using the MIP solver of ILOG CPLEX 8.1.

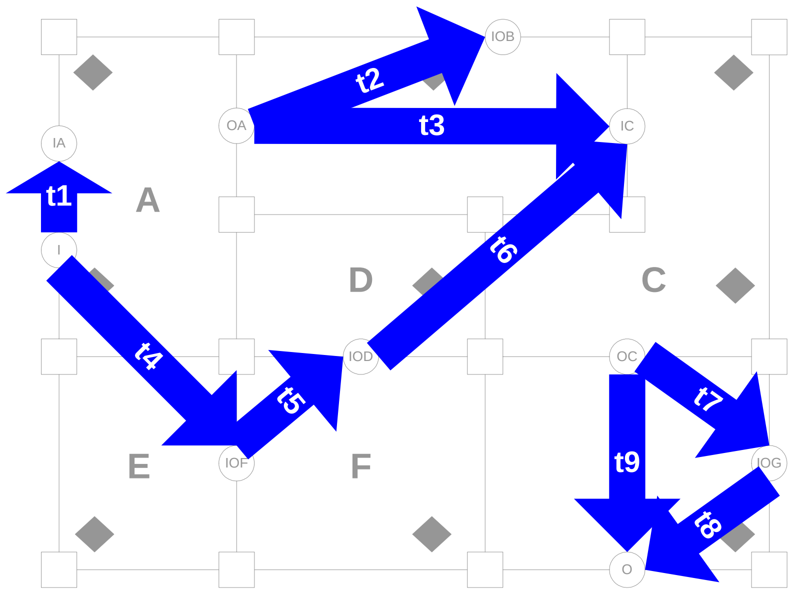

Figure 4-2: Nine Tasks of the Illustrative Example

Table 4-2: Compatibility of Tasks and Technology and Their Hourly Demands (unit-loads)

	e1	e2	e3	e4
t1	60	30	120	120
t2			90	90
t3			90	90
t4	50	25		
t5		25	100	100
t6		45	180	180
t7	60	60		
t8	60		120	120
t9	60	30		

Table 4-3: Speed and Hourly Costs of Example Technologies

	e1	e2	e3	e4
Speed	7 mph or 11.27 km/hr	3 mph or 4.83 km/hr	3 mph or 4.83 km/hr	3 mph or 4.83 km/hr
Network operating cost	$6.4286	$5.4762	$0.0698	$0.0198
Network construction cost	$0.5500	$4.4633	$1.6667	$2.1333

4.5.1 *The Impact of Tight Formulation*

The purpose of this experiment is to show the impact of the tight flow capacity constraint in Section 4.4.4. The only difference between the original and the tight formulations is that we replace constraint (4-10) by (4-10a) in the tight formulation. Note that the cost of the control systems is not included in this comparison. We summarize solution values and some computational statistics in Table 4-4.

Table 4-4: Computational Results of Original and Tight Formulations

Formulation		Original Formulation	Tight Formulation
Result		Optimal	Optimal
Solution Value		$122,261	$122,261
Initial Solution	Upper Bound	$134,648	$123,762
	Lower Bound	$106,619	$101,115
	Gap	20.82%	18.30%
Cuts Applied (by CPLEX)	Cover Cuts	122	139
	Flow Cuts	802	902
	Flow Path Cuts	1	0
	Gomory Fractional Cuts	3	5
Clock Time		1,476,380 sec. (410 hrs)	383,166 sec. (106 hrs)
Largest Tree Size (Mega Bytes)		540	176
Number of Nodes		86,500	30,100

Table 4-4 shows both formulations have the same optimal solution. The gap of initial solution provided by the tight formulation is smaller than the gap of the original formulation. Solving the example problem with the tight formulation requires only 26% of the time compared to the original formulation. The number of nodes required of the tight formulation in the branch and bound tree is also significantly less than the requirement of the original formulation. The details of convergence of tight and original formulation are shown in Figure 4-3.

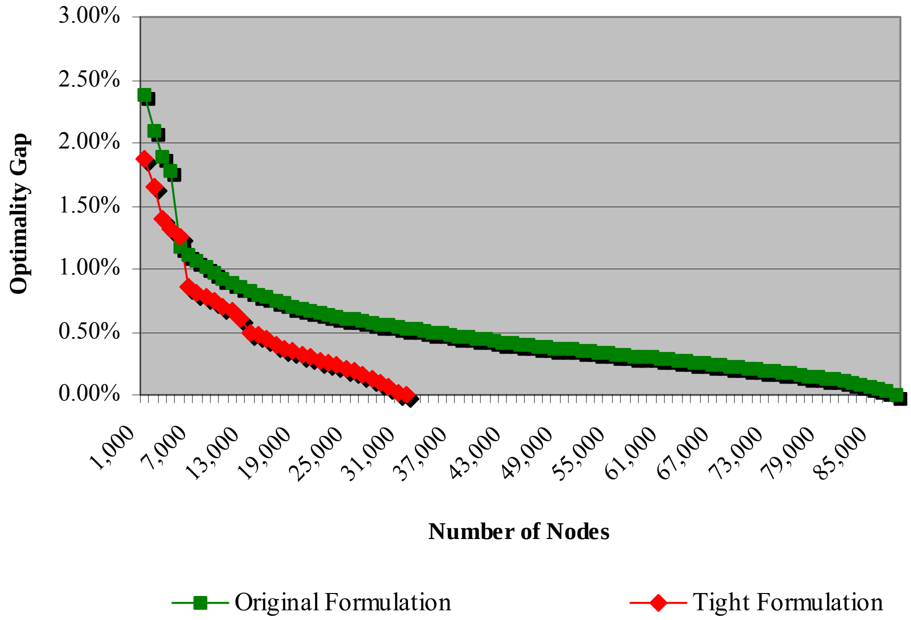

Figure 4-3: Convergence of Original and Tight Formulation

The optimal MTS design of both formulations is presented in Figure 4-4. A more detailed interpretation of this optimal design will be given in the next section.

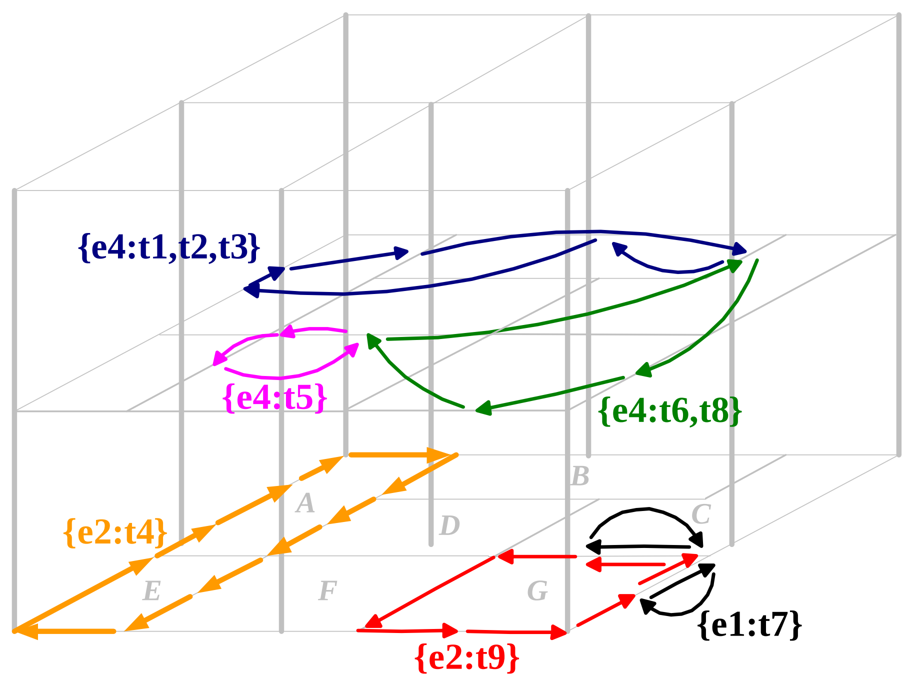

Figure 4-4: MTS Design by the CF Approach

4.5.2 The Impact of Control System Cost on System Selection

The second part of the experiments is to study the impact of control system cost on the task clustering of MTS design. In this research, we model the control system cost of transport (sub)systems by two elements, fixed cost and incremental cost. A fixed cost is incurred once a technology is chosen and an incremental cost is charged according to the number of tasks included. Since the cost of a control system is relatively independent of geographical location, travel distances and flow intensities of transport tasks, a high control system cost should prevent single-task clusters and lead to more task aggregation.

To demonstrate this effect, we prepared four cost scenarios for control systems as shown in Table 4-5. Scenario 0 ignores the cost of the control system. Scenario 1 has a relatively low cost, scenario 2 has a moderate cost, and scenario 3 has a high cost for each example technology. Note that the fixed and incremental costs of the control system are amortized over five years and expressed on a daily basis to be consistent with other cost elements.

Table 4-5: Four Cost Scenarios for Control Systems

		Control Cost Scenarios			
		Scenario 0	Scenario 1	Scenario 2	Scenario 3
Technology e1	Fixed	$0	$13.33	$133.3	$1333
	Incremental	$0	$6.67	$66.7	$667
Technology e2	Fixed	$0	$66.67	$666.7	$6667
	Incremental	$0	$13.33	$133.3	$1333
Technology e3	Fixed	$0	$66.67	$666.7	$6667
	Incremental	$0	$13.33	$133.3	$1333
Technology e4	Fixed	$0	$33.33	$333.3	$3333
	Incremental	$0	$13.33	$133.3	$1333

The optimal MTS designs of these four scenarios are presented in Figure 4-5, Figure 4-6, Figure 4-7, and Figure 4-7, respectively. As shown in Figure 4-5, the optimal MTS design of scenario 0 contains six sub-systems. Task 7 is serviced by counter-balance lift truck and its flow network is shown by black solid arrows. Task 4 is serviced by unit-load AGV and its flow network is shown by orange solid arrows. Task 9 is serviced by unit-load AGV and its flow network is shown by red solid arrows. Task 5 is serviced by overhead trolley conveyor and its flow network is shown by pink solid arrows. Tasks 6 and 8 are serviced by overhead trolley conveyor and their flow network is shown by green solid arrows. Tasks 1, 2 and 3 are serviced by overhead trolley conveyor, and their flow network is shown by blue solid arrows.

In scenario 0, we have two task clusters with multiple tasks. A multiple-task cluster shares the transport carriers with other tasks in the cluster. In this scenario, carriers of overhead trolley conveyor might be called to service task 8 after task 6 is done or vice versa. As shown in Figure 4-6, the MTS design of scenario 1 is exactly the same as the design of Scenario 0. Figure 4-6 shows the optimal MTS design of scenario 2. Notice that task 5, instead of being a single-task cluster, is included in task cluster with tasks 1, 2 and 3, and their flow network is shown by blue solid arrows. In Figure 4-7, we can see that the number of task clusters is further reduced to 4 by combining tasks 4 and 9 into the same cluster. Tasks 4 and 9 are serviced by unit-load AGV through the flow network represented in red solid arrows.

The task clustering of the four cost scenarios of control systems is summarized in Table 4-6. The total number of task clusters is reduced from six to four with the increasing costs of control system. From this experiment we can learn that single-task solutions might not be economical, especially when the costs of control system are significant.

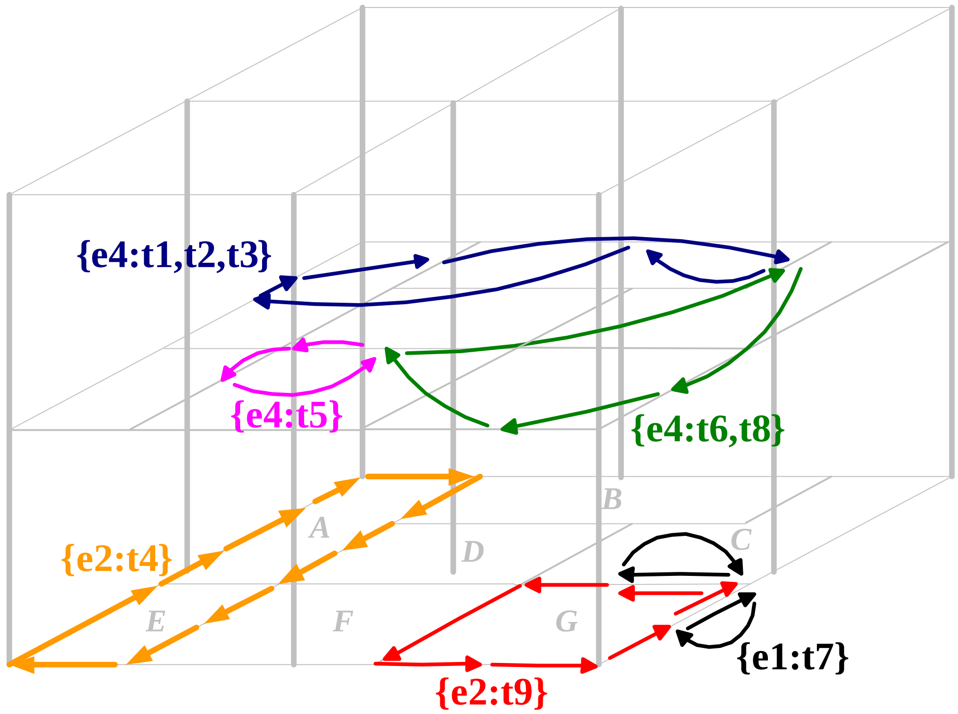

Figure 4-5: MTS Design by the CF Approach with Control Cost Scenario 1

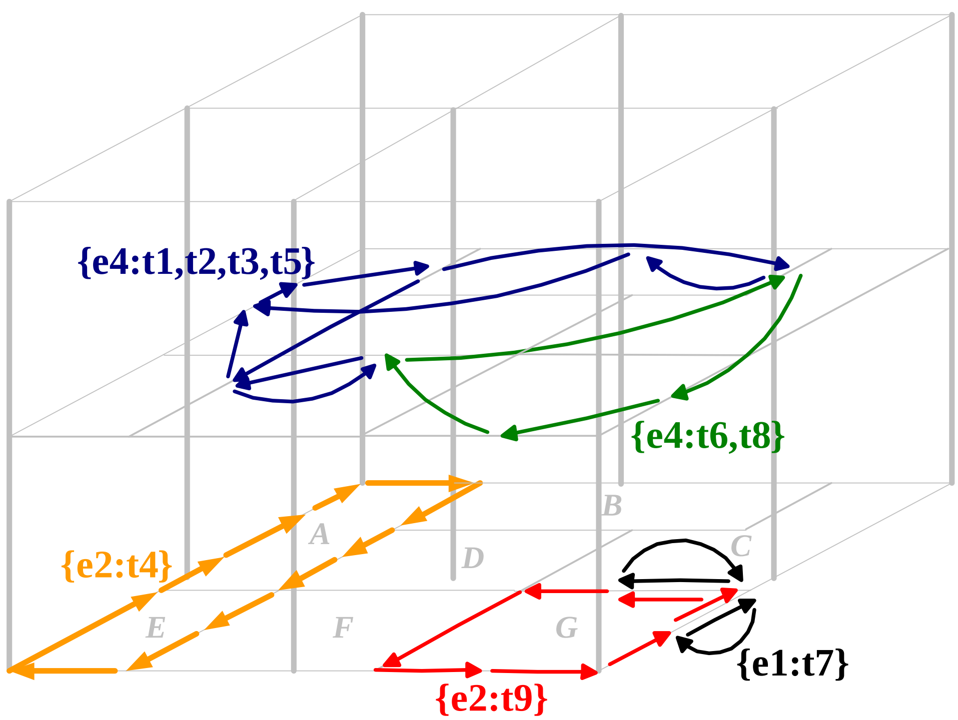

Figure 4-6: MTS Design by the CF Approach with Control Cost Scenario 2

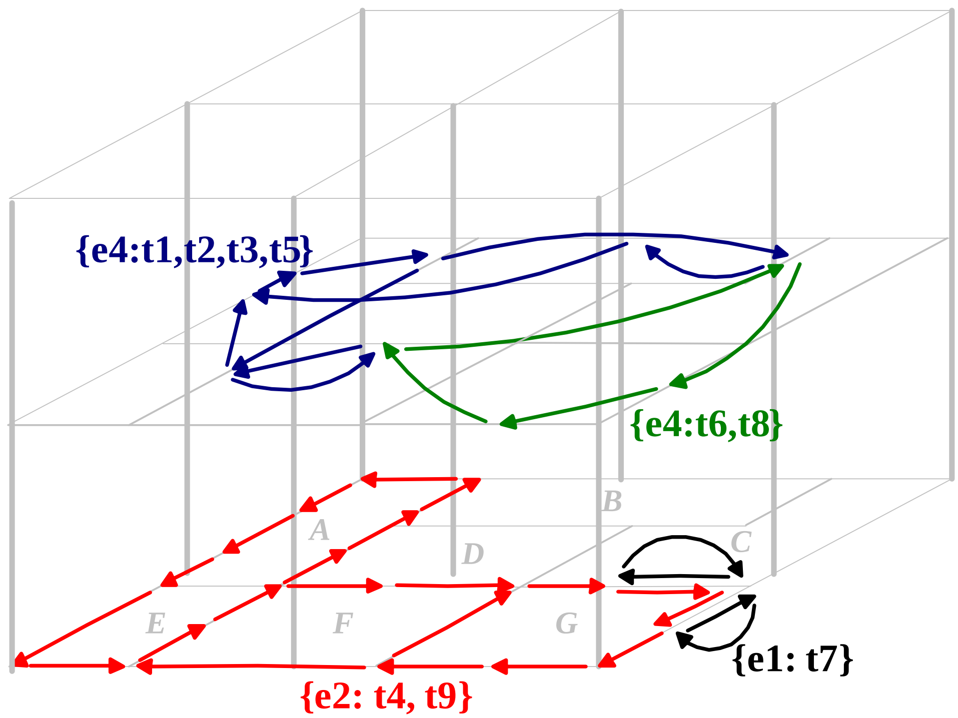

Figure 4-7: MTS Design by the CF Approach with Control Cost Scenario 3

Table 4-6: Summary of Task Clustering of Four Control Cost Scenarios

		Control Cost Scenarios			
		Scenario 0	Scenario 1	Scenario 2	Scenario 3
Task Clusters	Cluster 1	{t7}	{t7}	{t7}	{t7}
	Cluster 2	{t4}	{t4}	{t4}	{t4, t9}
	Cluster 3	{t9}	{t9}	{t9}	{t6, t8}
	Cluster 4	{t5}	{t5}	{t6, t8}	{t1, t2, t3, t5}
	Cluster 5	{t6, t8}	{t6, t8}	{t1, t2, t3, t5}	{}
	Cluster 6	{t1, t2, t3}	{t1, t2, t3}	{}	{}

4.6 Concluding Remarks

In this chapter, we introduce a compact formulation of MTSDP by modeling it as a Mixed Integer Nonlinear Programming problem. The validity of this formulation is verified by the requirements of MTS designs. Some linearization techniques are applied to make the proposed model a linear one. The linear approximation generally underestimates empty flow by violating empty travel ratio of Kuhn's representation but the desired solution requirements can still be guaranteed by exploring the problem structure and properties of empty travel technique.

The number of variables and constraints of the proposed formulation grows fast with some characteristics of the problems. Therefore, a tighter formulation is proposed to reduce solution time. By the experiments with an illustrative example provided in Section 4.5, we show that

- The proposed formulation provides solutions that answer the questions of MTSDP (except for the violation of empty travel ratio in linear approximation),
- The tight formulation reduces the solution time, e.g., the solution time of the tight formulation is 3.85 times faster than the solution time of the original formulation, and
- With the presence of significant cost of control system, the designs with multiple-task cluster are more economical than the designs restricted to only single-task clusters.

Although the solution time is being significantly reduced by the tight formulation, the expected solution time of the compact formulation approach with industrial problem sizes is still considerably long. Therefore, there is a need to develop a different approach that shortens the solution time without sacrificing the integrated concerns of MTSDP. Such approach will be introduced in the next chapter.

CHAPTER 5

A CLUSTERING/ SET PARTITION APPROACH TO THE MTSDP

In this chapter we propose a clustering/set partition (CSP) approach for the integrated MTS design problem. This approach consists of three phases, given the compatibilities between individual tasks and technologies. The first phase, clustering, is to associate task clusters with compatible technologies. A set of task clusters then passes to the second phase. Connecting tasks within cluster by viable technology flow networks leads to feasible tasks-resource combinations. The last phase of this approach chooses an economical subset of combinations that satisfy the assignment and availability requirements.

Figure 5-1 demonstrates this solution framework. The gray-line boxes represent the information types and the dashed lines indicate information flows. The bold-line boxes and bold lines represent the decision components and their sequences. Essentially, this three-phase approach deals with the decomposed optimization problem of material transport system (MTS) design. This three-phase approach provides an alternative to the compact formulation approach proposed in CHAPTER 4.

This chapter is organized as follows: We briefly introduce the concepts, attributes and methodologies used for clustering tasks in section 5.1. In section 5.2, the technology dependent requirements of the decomposed MTSDP at the connecting phase will be introduced. Clustering and flow network design methods used to construct feasible tasks-resource combinations will also be discussed in detail. When the validity of technology dependent requirements is ensured, we will illustrate the system selection with global requirements in section 5.3. In section 5.4, we demonstrate the results of computational experiments and the comparisons of integrated MTSDP approaches and traditional approaches in literature. Section 5.5 summarizes this chapter.

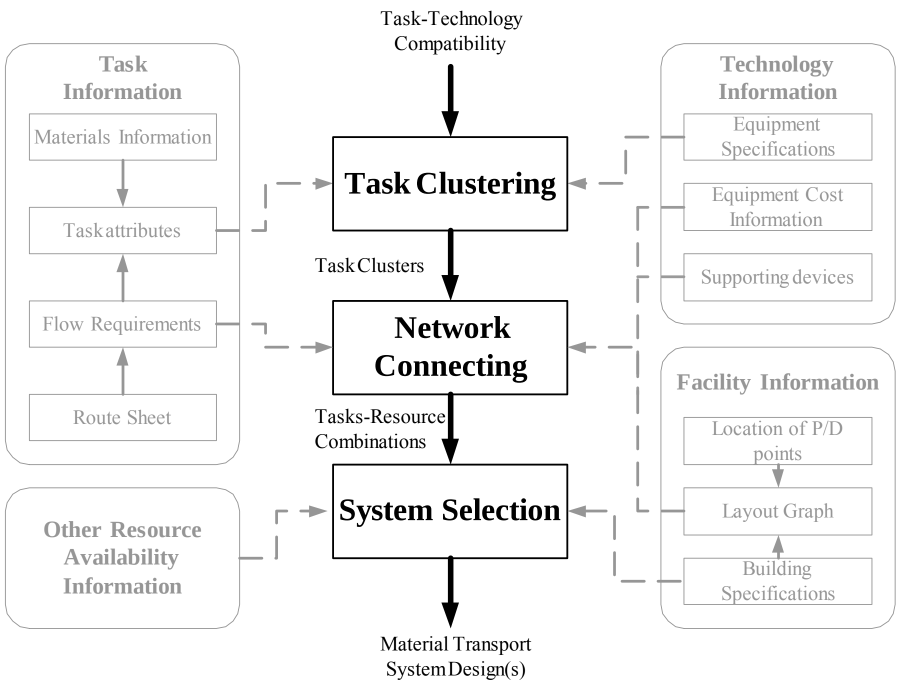

Figure 5-1: The Proposed Clustering/Set Partition Approach for MTSDP

5.1 Task Clustering

Consider a MTS design as a set of material transport subsystems. Each subsystem that can be seen as a tasks-resource combination, consists of three elements: tasks, technology, and the flow network. If we could enumerate all possible combinations, the MTSDP simply becomes a selection problem subject to some system requirements.

Given the compatibilities between individual tasks and technologies, the purpose of clustering and connecting is to construct feasible tasks-resource combinations. Each row of the compatibility matrix represents the compatibility between a specific technology e and task $t \subseteq T$. Denote the set of compatible tasks for technology e as

$T(e) \subseteq T$. The problem of constructing feasible tasks-resource combinations can be stated as: Given a set of tasks $T(e)$ and the corresponding working network of technology e, find a set of task clusters $T(k)$'s, where $T(k) \subseteq T(e)$, such that the flow network for elements belonging to $T(k)$ satisfies the relevant network restrictions.

The construction of feasible tasks-resource combinations for a technology e on its working network is, although simple in concept once specified, difficult in general because of the following reasons: a cost function with fixed charge, competition for system resources, network restrictions, and the allocation of empty flow.

Because of the complexity of constructing feasible tasks-resource combinations, we further decompose this construction problem into clustering and connecting steps. The number of all possible combinations may be so large that we can only generate a subset of them. Given a set of compatible tasks $T(e)$, where $|T(e)| = a$, for a technology e, the number of possible combinations for these tasks is $\sum\left\{\binom{a}{i} : i = 1,\ldots,a\right\}$, where $\binom{a}{i}$ stands for the number of combinations of a choose i. For example, if a = 20, 30, and 40, the possible combinations are about 1.05×10^{6}, 1.07×10^{9}, and 1.1×10^{12}, respectively. Moreover, difficulties come from not only the number of possible combinations, but also the lack of a structure to evaluate these combinations from the perspective of system requirements. Therefore, restricting the output of the clustering and connecting steps to some ”promising” task-resource combinations is our way to deal with this difficulty.

As mentioned earlier, one of the motivations for grouping transport requests is the sharing of the significant fixed costs of a sub-system to achieve economy of scale. Because of the importance of travel distance to the cost function, the clustering of tasks could be based on origin/destination coordinates to form sets of tasks with minimal empty travel. Another important factor affecting variable cost is the product of travel distance and the intensity of flow. Base on these cost-affecting factors we provide three clustering criteria as follow, given two tasks t and k, and their coordinates.

- The proximity of [$o(t)$ and $o(k)$] and [$d(t)$ and $d(k)$]
- The proximity of [$d(t)$ and $o(k)$] and [$d(k)$ and $o(t)$]
- The proximity of weighted distance

The first two criteria aim at merging and chaining tasks whose origins and destinations are close to each other. The third criterion takes the product of travel distance and the intensity of flow based on Kuhn's empty travel representation. The pair-wise weighted distance formula is as follows:

$$\text{flow}(t)\times\left[\text{dist}(o(t),d(t))+\frac{\text{flow}(t)}{\text{flow}(t)+\text{flow}(k)}\times\text{dist}(d(t),o(t))+\frac{\text{flow}(k)}{\text{flow}(t)+\text{flow}(k)}\times\text{dist}(d(t),o(k))\right]+$$
$$\text{flow}(k)\times\left[\text{dist}(o(k),d(k))+\frac{\text{flow}(k)}{\text{flow}(t)+\text{flow}(k)}\times\text{dist}(d(k),o(k))+\frac{\text{flow}(t)}{\text{flow}(t)+\text{flow}(k)}\times\text{dist}(d(k),o(t))\right]$$

Note that the distance metric used to evaluate the proximity of two tasks can differ with the transport technologies. Since the flow network is not available at this phase, Euclidean, Rectilinear, and Chybechev metrics are used to approximate the closeness of tasks.

Given the distances (or similarities) of every pair of tasks, we use agglomerative hierarchical clustering procedures (see Anderberg (1973) for details) to generate a set of task clusters. The agglomerative hierarchical clustering procedure starts with each task as a cluster and with each step combines clusters until there is only one cluster that has all the tasks. There are various methods to evaluate the distances between two task clusters. In this research, we use following three methods:

- Single linkage: Compute the distance of every pair of tasks with one task in each cluster. Compute the shortest distance and let this be the distance of the clusters.
- Average linkage: Compute the distance of every pair of tasks with one task in each cluster. Compute the average distance; let this be the distance of the clusters.
- Complete linkage: Compute the distance of every pair of tasks with one task in each cluster. Compute the largest distance; let this be the distance of the clusters.

In this research, we use clustering analysis of MINITAB 14 based on the proposed clustering criteria, and we take the union of the results of three hierarchical clustering procedures to form a set of task clusters.

Note that the separation of the clustering decisions and flow network designs also helps us to estimate the empty flow in advance by predetermining the destinations of empty flow. As discussed in Section 4.2.3, the elusiveness of empty travel approximation in the compact formulation comes from the simultaneous decisions of task clustering and flow network designs. If task clustering is given, we can preprocess the empty travel by some approximation techniques and treat empty travel as additional flow requirement. For example, consider tasks $t1$ and $t2$ and apply Kuhn's empty travel approximation. If $t1$ and $t2$ each forms its own cluster, the empty travel requirements are simply F_{t1} from destination of $t1$, d(t1), to origin of task 1, $o(t1)$; and F_{t2} from destination of $t2$, $d(t2)$, to origin of task 2, $o(t2)$. On the other hand, if $t1$ and $t2$ are together in a cluster $\{t1, t2\}$, then the empty flows would be compacted as in Section 4.2.3.

5.2 Network Connecting

Given a task cluster, the purpose of constructing a network for the tasks in the cluster is twofold. The first is to make sure that the technology under consideration can be implemented on the resulting network to serve these tasks. The second is to approximate the costs of the tasks-resource combination. To achieve this end, the importance of a realistic cost structure cannot be overemphasized. As shown in Appendix A, the network related resource units needed for each combination can be translated into cost coefficients of the objective function, reflecting both fixed costs and variable costs of network operation.

A feasible tasks-resource combination must satisfy the technology dependent requirements introduced in Section 4.3.2, requirements 2, 3, 4, 5 and 6. The connecting phase involves flow network design for six different types of working network topology: manually driven vehicle, automated guided vehicle, floor-supported conveyor, overhead trolley conveyor, overhead power-and-free conveyor, and bridge crane. To construct feasible networks for a technology to serve the tasks in a cluster, the following constraints apply:

- Flow capacity constraint on each network segment. Combinations in technology class E^B (bridge crane) are capacitated in total travel time. Note that the aggregation of tasks might result in long queue times or large WIP inventory. Some capacity can be reserved to cope with the situation of resource over-utilization, e.g., set the maximum utilization of a certain resource to 85% of its limit. We assume there is no congestion within the capacity limit once the arc fixed charge is incurred.
- Directionality constraints. The network directionality constraints maintain unidirectional travel on an arc for some technologies. The restriction on bi-directional travel for some technologies arises from operational concerns, e.g., as in an AGV system, and also mechanical capability, e.g., floor level and overhead conveyors.

- Connectivity. The connectivity constraints are intended to provide a connected network so that the technology can reach the origins and destinations of the designated tasks. As shown in Table 3-3, there are different types of connectivity restrictions among technologies.

In order to further discuss the network connecting step of the proposed approach, we formulate the flow network design problem (FNDP in short) as a mixed integer program in a general sense (as shown in Figure 5-2). The term “general” applies to the required information and subset of constraints. Note that FNDP is a variant of the fixed-charge, capacitated, multicommodity network design problem (Magnanti and Wong (1984), Minoux (1989)).

Given a set of tasks T including the empty travel approximated by Kuhn’s representation, cost data and specifications (C_{ij}^{v}, C_{ij}^{f}, U_{ij}) of the technology under consideration, and a working network $G = (N, A)$, FNDP selects arcs to be included in the resulting network, the orientation of each arc, and the flow on each arc, so that the sum of the costs is minimized.

$$\text{Minimize } Z(\text{f}, \text{y}) = \sum_{(i,j)\in A} C_{ij}^{f} y_{ij} + \sum_{(i,j)\in A} C_{ij}^{v} \sum_{t\in T} f_{ijt}$$

$$\text{Subject to} \quad \sum_{j:(i,j)\in A} f_{ijt} - \sum_{j:(j,i)\in A} f_{jit} = \begin{cases} F_t & , \text{ if } i = o(t) \\ -F_t & , \text{ if } i = d(t), \\ 0 & , \text{ otherwise} \end{cases} \quad \text{for any } i \in N, \text{for any } t \in T$$

$$\sum_{t\in T} f_{ijt} \le U_{ij} y_{ij}, \quad \text{for any } (i,j) \in A$$

$$\text{y} \in Y$$

$$f_{ijt} \ge 0, \quad \text{for any } (i,j) \in A, \text{for any } t \in T$$

$$y_{ij} = \{0,1\}, \quad \text{for any } (i,j) \in A$$

Figure 5-2: A General Flow Network Design Formulation

The objective function minimizes the lifetime costs that are related to network construction and operation. The first constraint maintains the flow balance at each node. The second constraint keeps the flow on arc (i, j) within its capacity U_{ij} and prohibits flow on arcs that are not included in the solution. The third constraint is a general representation of the topology constraints associated with a specific technology class. The topology constraints for each specific technology class are discussed in the following sections.

5.2.1 Flow Network Design Problems for Technology Class E^{VM}

The flow network design problems for manually driven vehicle technology $e \in E^{VM}$, FNDP(E^{VM}) in short, are subject to flow capacity and strong connectivity constraints. A feasible solution must possess a path from every origin to the destination of any task in the cluster. This strong connectivity is guaranteed by Kuhn's empty travel representation and flow balance constraints (Observation 1 in Section 4.3.2). The formulation of FNDP(E^{VM}) can be obtained by specifying the constraint set $Y = \{ \}$ and replacing the input information as follows:

- $T = T(k)$, where $T(k) \subseteq T(e)$
- $G = G_e^V$
- $C_{ij}^v = C_{ij}^v$ (VM), $C_{ij}^f = C_{ij}^f$ (VM)
- $U_{ij} = U_{ije}$

5.2.2 Flow Network Design Problems for Technology Class E^{VA}

The flow network design problems for automated vehicle technology $e \in E^{VA}$, FNDP(E^{VA}) in short, are subject to flow capacity, strong connectivity and unidirectional constraints. Since the strong connectivity is guaranteed by Kuhn's empty travel representation and flow balance constraints, the formulation of FNDP(E^{VA}) can be obtained by specifying the constraint set Y = $\{ y_{ij} + y_{ji} \le 1$, for any $(i, j) \in A$ and $i < j \}$ and replacing the input information as follows:

- $T = T(k)$, where $T(k) \subseteq T(e)$
- $G = G_e^V$
- $C_{ij}^v = C_{ij}^v$ (VA), $C_{ij}^f = C_{ij}^f$ (VA)
- $U_{ij} = U_{ije}$

5.2.3 Flow Network Design Problems for Technology Class E^C

The flow network design problems for conveyor technology $e \in E^C$, FNDP(E^C) in short, are subject to flow capacity, weak connectivity requirements and unidirectional constraints. Since we do not consider empty travel in a typical floor-supported conveyor, the weak connectivity can be obtained by flow requirements. The formulation of FNDP(E^C) can be obtained by specifying the constraint set Y = $\{ y_{ij} + y_{ji} \le 1$, for any $(i, j) \in A$ and $i < j \}$ and replacing the input information as follows:

- $T = T(k)$, where $T(k) \subseteq T(e)$
- $G = G_e^C$
- $C_{ij}^v = C_{ij}^v$ (C), $C_{ij}^f = C_{ij}^f$ (C)
- $U_{ij} = U_{ije}$

5.2.4 Flow Network Design Problems for Technology Class E^{OP}

The flow network design problems for overhead power-and-free technology $e \in E^{OP}$, FNDP(E^{OP}) in short, are subject to flow capacity, strong connectivity and unidirectional constraints. Since the strong connectivity is guaranteed by Kuhn's empty travel representation and flow balance constraints, the formulation of FNDP(E^{OP}) can be obtained by specifying the constraint set $Y = \{ y_{ij} + y_{ji} \leq 1$, for any $(i, j) \in A$ and $i < j \}$ and replacing the input information as follows:

- $T = T(k)$, where $T(k) \subseteq T(e)$
- $G = G_e^O$
- $C_{ij}^v = C_{ij}^v$ (OP), $C_{ij}^f = C_{ij}^f$ (OP)
- $U_{ij} = U_{ije}$

5.2.5 *Flow Network Design Problems for Technology Class E^{OT}*

The flow network design problems for overhead trolley technology $e \in E^{OT}$, FNDP(E^{OT}) in short, are subject to flow capacity, unidirectional constraints and closed trail. The unidirectional constraints and closed trail of FNDP(E^{OT}) can be obtained (Observation 2 in Section 4.3.2) by specifying the constraint set

$$Y = \left\{ \begin{array}{l} y_{ij} + y_{ji} \leq 1, \text{for any } (i, j) \in A \text{ and } i < j \\ \sum_{j:(i,j)\in A} y_{ij} - \sum_{j:(j,i)\in A} y_{ji} = 0, \text{for any } i \in N \end{array} \right\},$$

and replacing the input information as follows:

- $T = T(k)$, where $T(k) \subseteq T(e)$
- $G = G_e^O$
- $C_{ij}^v = C_{ij}^v$ (OT), $C_{ij}^f = C_{ij}^f$ (OT)
- $U_{ij} = U_{ije}$

5.2.6 Flow Network Design Problems for Technology Class E^B

Once the task cluster $T(k)$ is specified, the flow network design problem for technology $e \in E^B$ is relatively straightforward:

For each tasks-resource combination,

1. Check if the capacity constraints are satisfied?

   $\sum(F_t f_{ijt} L_\infty(i, j) : i = o(t), j = d(t)$, for any $t \in T(k)) \leq U_e$

2. Obtain the minimum number of rectangles that cover all the pickup and delivery points and check if the concatenation of these rectangles is a rectangle?
3. Check if the concatenated rectangle contains no column nodes?

If the answers to the above three checks are all positive, the combination is feasible. Otherwise, it is not a feasible combination for technology $e \in E^B$ and the tasks-resource combination must be rejected. The flow network is the concatenated rectangle and its related cost of network design can be obtained as shown in Appendix A.

5.3 System Selection

The last step of the proposed approach is to form a MTS design from the set of tasks-resource combinations provided in the task clustering and network connecting steps. The MTS design must respect the assignment constraints and availability constraints (requirements 1 and 4 in Section 4.3.2). A tasks-resource combination k can be represented as quadruple $(e_k, \mathrm{T}(k), G_k^e, C_k)$, where e_k denotes the technology employed, $T(k)$ records the tasks included, G_k^e contains a set of nodes and arcs that form the network, and C_k is the cost of network construction and operating.

In general, the system selection problem can be formulated as a binary integer program (a variation of the set partition problem). Given a finite set of tasks-resource combinations K, prepare a $|T| \times |K|$ task-combination matrix **A**. An element of the task-combination matrix a_{tk} is set to 1 if task t is included in combination k and 0 otherwise. The objective of system selection is to minimize the total costs of the chosen tasks-resource combinations subject to assignment and availability constraints.

The binary integer programming model of the system selection step of MTSDP (as shown in Figure 5-3) can be stated as follows: The objective function minimizes the sum of network structure cost, network operations, and fixed and incremental costs of control systems. The first constraint ensures that each task is served by exactly one technology. Additional constraints deal with availability of resources. Common resource availability constraints used in MTSDP are discussed in the subsections below. Note that the following modeling variations can also be accommodated in the compact formulation approach in CHAPTER 4.

$$\text{Minimize } Z(\text{w}) = \sum_{k \in K} ((C_{e_k}^{\text{C1}} + C_{e_k}^{\text{C2}} \sum_{t \in T} a_{tk} + C_k) w_k$$

$$\text{Subject to} \quad \sum_{k \in K} a_{tk} w_k = 1, \quad \text{for any } t \in \text{T}$$
$$w \in \text{W}$$
$$w_k = \{0,1\}, \quad \text{for any } k \in K$$

Figure 5-3: A General System Selection Formulation

5.3.1 Capital Investment

The capital investment of a MTS design is limited to B dollars. Denote the capital investment of a tasks-resource combination k as CC_k. Note that the capital investment of a combination can be obtained from the corresponding cost model in Appendix A. Given the capital expenditure for each combination; the capital investment constraint of a MTS design can be stated as follows:

$$\sum_{k \in K} CC_k w_k \leq B$$

5.3.2 Path Width Constraints

The width consumed on flow path segment (i, j) of a MTS design cannot exceed L_{ij}. Denote the required space for combination k on arc (i, j) as h_{ijk}. The path width constraint of a set of arcs $A^{'}$ can be stated as follows:

$$\sum_{k \in K} h_{ijk} w_k \leq L_{ij}, \text{ for any } (i, j) \in A^{'}$$

5.3.3 Flow Path Crossing Constraints

There may be a restriction on flow path crossing between two technologies on a segment of the aisle network. This type of restriction typically applies at the floor level conveyor network and aisle network, due to the sharing of common space. If a floor level conveyor crosses the boundary of a workstation, the potential aisle is blocked by the conveyor. To prevent undesirable flow path crossing, the working network of conveyor needs to be modified so that the crossing can be specified explicitly. A possible modification to serve this purpose is provided through a case problem in CHAPTER 6.

5.4 Computational Experiments

In this section, we perform computational experiments on the proposed CSP approach and compare the results with those of other approaches.

The first experiment focuses on the comparison of solutions between the CSP approach and one conventional approach in the literature. As discussed in CHAPTER 2, previous research treated essential and interrelated elements of material transport system design as isolated problems. The comparisons of solutions between the CSP approach and the conventional one can help us understand the importance of studying integrated MTS design problems and approaches.

The second experiment studies the computational performance and solutions of two proposed approaches for the integrated MTS design problems. The illustrative example used for the experiments in Section 5.4.2 is the same as the example in Section 4.5. The compact formulation (CF in short) approach proposed in CHAPTER 4 provides an approximation for MTS design problems. By comparing the optimal solution provided by enumeration on a small example, we can evaluate the quality of solution provided by the CF and the CSP approaches.

The computations for the CF approach are done on a Sun workstation 220R with 2x360MHz UltraSparc II CPU's and 2GB RAM. The computations for the enumeration and the CSP approach are done on a PC with 700 MHz Pentium III CPU and 512 MB RAM. We solve all optimization problems of the MTSDP by using the MIP solver of ILOG CPLEX 8.1.

5.4.1 The CSP Approach versus Conventional Approach

In this section, we compare the results of a greedy approach (GREEDY in short) and the proposed CSP approach. We briefly introduced the GREEDY approach in Section 2.1.3 and 2.3. In terms of the material transport system design problem, GREEDY selects transport technologies by considering only loaded travel requirements with centroid-to-centroid origin-destination (O-D) definition and Euclidean distance metric. For better illustration of GREEDY, we adopt pickup-to-delivery points O-D definition and calculate the loaded travel distances with rectilinear distance metric for vehicle-based technologies and Euclidean distance metric for conveyor-based technologies. The hourly-loaded travel requirements and specifications/costs of candidate technologies are provided in Table 4-2 and Table 4-3. The two-dimensional coordinates, Euclidean and rectilinear distances of each task are provided in Table 5-1. By applying GREEDY and considering variable and fixed costs of network operation, we summarize the least cost technology selection of each task and its corresponding cost in columns 2 and 3 of Table 5-2

Table 5-1: Coordinates and Distances of Tasks

	Origin		Destination		Euclidean	Rectilinear
	x	y	x	y		
t1	160	70	160	90	20.00	20.00
t2	120	95	65	120	60.42	80.00
t3	120	95	35	95	85.00	85.00
t4	160	70	120	20	64.03	90.00
t5	120	20	75	40	49.24	65.00
t6	75	40	35	95	68.01	95.00
t7	35	40	0	20	40.31	55.00
t8	0	20	35	0	40.31	55.00
t9	35	40	35	0	40.00	40.00

We also apply the proposed CSP approach on the same example. Due to the small size of this example, we can obtain the optimal solution by enumeration. Except for technology $e1$ that has five eligible tasks, the other technologies, $e2$, $e3$ and $e4$ each have six eligible tasks, respectively. There are 220 ($\sum\left\{\binom{5}{i} : i = 1,...,5\right\} + 3\sum\left\{\binom{6}{i} : i = 1,...,6\right\} = 220$) possible combinations of tasks-technology. By applying Kuhn's empty travel representation, we can get all the loaded and empty travel requirements. Then, we solve 220 flow network design problems based on the technologies and the corresponding working networks. Given 220 tasks-technology combinations and their network costs, we can formulate a set-partition problem and solve it to get the optimal MTS design of this example. Note that the overhead working networks of power and free conveyor ($e3$) and trolley conveyor ($e4$) are slightly different in this section. Instead of one bi-directional arc associated with every pair of nodes, we assume there are two bi-directional arcs associated with every pair of nodes in the overhead working networks of *e*3 and *e*4.

In order to make a fair comparison, we put the results of the three approaches (GREEDY, CSP, Enumeration) on the same basis. Since we have flow network designs of all combinations formed by considering empty travel, and following the working networks of technologies, we take the technology assignments of GREEDY and match them to the corresponding flow network designs. Columns 1, 2, and 3 of Table 5-2 indicate the tasks, their technology assignments and their costs by GREEDY. Columns 4 and 5 of Table 5-2, CLUSTER and COST, record the corresponding clusters and costs of flow network designs of GREEDY technology assignments: {*e*4: *t*1} means task 1 is assigned to technology *e*4.

The differences between the costs of GREEDY and CLUSTER in Table 5-2 are the inclusion of empty travel and the design of working networks. Take task *t*9, the one with the largest difference, for example. As shown in Figure 5-4, the rectilinear distance between the origin (node 5) and destination (node 11) is 40 ft. Task *t*9 requires 30 units technology *e*2 per day. The daily operating cost is $5.48 per foot per unit technology, and the amortized daily network construction cost is $4.46 per foot. The total cost for technology *e*2 to service task *t*9 by GREEDY approach is $6,749.96 per day. By introducing the empty travel requirements and the working network of technology *e*2, the network design for technology *e*2 to service task *t*9 is shown with black solid arrows in Figure 5-4. The total distance of this network design is 220 ft and the total cost for technology *e*2 to service task *t*9 by the CSP approach is $37,124.80 per day. The cost breakdown of the two approaches for this sub-system is provided in Table 5-3

Table 5-2: Translation of Solutions from GREEDY to CSP

1	2	3	4	5
	GREEDY	COST (GREEDY)	CLUSTER	COST
t1	e4	$90.29	{e4:t1}	$180.37
t2	e4	$236.77	{e4:t2}	$626.45
t3	e4	$333.12	{e4:t3}	$783.06
t4	e2	$12,723.13	{e2:t4}	$45,237.90
t5	e4	$202.76	{e4:t5}	$329.06
t6	e4	$387.97	{e4:t6}	$1,025.51
t7	e2	$18,316.91	{e2:t7}	$73,267.73
t8	e4	$181.98	{e4:t8}	$450.93
t9	e2	$6,749.96	{e2:t9}	$37,124.80

Table 5-3: Cost Breakdown of Sub-system for Task t9

	GREEDY	CSP
Network Distance	40 ft	220 ft
Operating Cost of Loaded Travel	$6571.43	$18,071.43
Operating Cost of Empty Travel	0	$18,071.43
Network Construction Cost	$178.53	$981.94
Total Cost	$6,749.96	$37,124.80

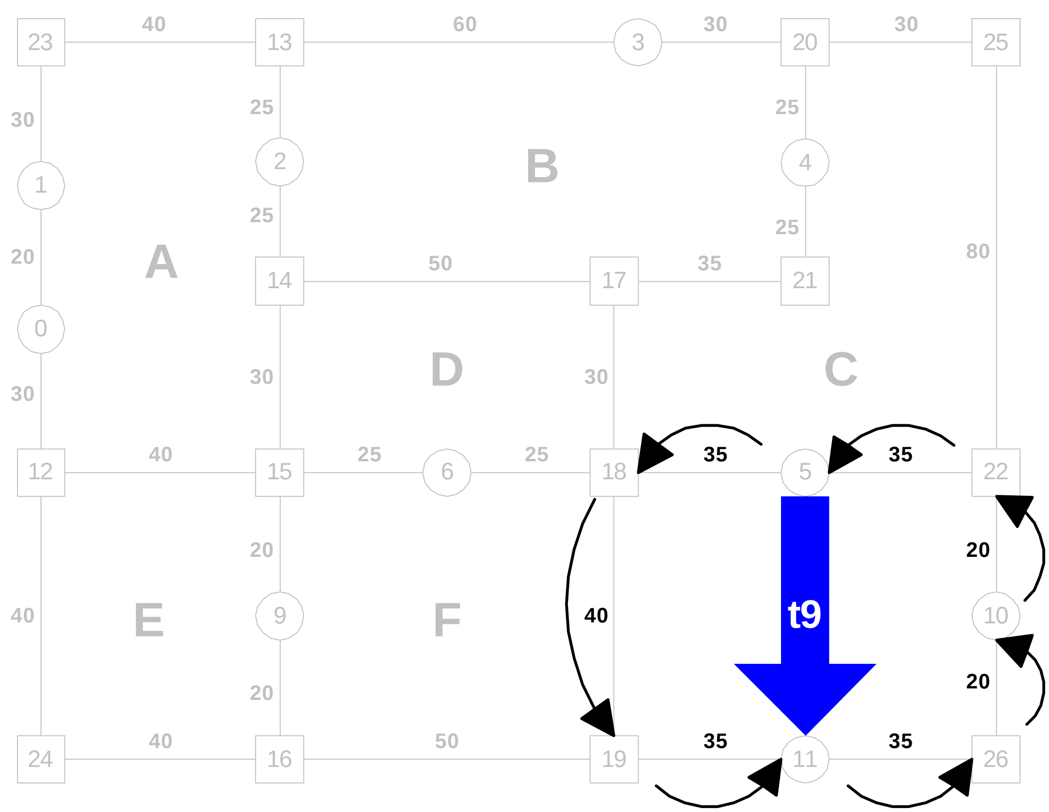

Figure 5-4: Sub-system Design of Example Problem

The solutions of GREEDY, CSP, and enumeration on this example are provided in Table 5-4. Column 2 of Table 5-4 summaries the task-technology assignments of GREEDY and their corresponding costs in flow network design. Column 3 of Table 5-4 records the task-technology assignments of CSP and their costs. The optimal task-technology assignments and their costs by enumerating all possibilities of this MTS design problem are summarized in column 3 of Table 5-4. Note that we only record cost at the first task for combinations that have multiple tasks. The total cost of GREEDY approach of this MTS design problem is $159,025.80. Compared to the optimal solution by enumeration, the GREEDY approach yields a solution that is 31.35% greater. In this example MTS design problem, the proposed CSP approach finds the optimal solution.

Table 5-4: Comparison of Solutions of GREEDY, CSP and Enumeration

1	2		3		4	
	CLUSTER/GREEDY		CSP		Enumeration	
	CLSTR	COST	CLSTR	COST	CLSTR	COST
t1	{e4:t1}	$180.37	{e4:t1}	$180.37	{e4:t1}	$180.37
t2	{e4:t2}	$626.45	{e4:t2,t3}	$1303.10	{e4:t2,t3}	$1303.10
t3	{e4:t3}	$783.06	{e4:t2,t3}		{e4:t2,t3}	
t4	{e2:t4}	$45,237.90	{e2:t4}	$45,237.90	{e2:t4}	$45,237.90
t5	{e4:t5}	$329.06	{e4:t5}	$329.06	{e4:t5}	$329.06
t6	{e4:t6}	$1,025.51	{e4:t6}	$1,025.51	{e4:t6}	$1,025.51
t7	{e2:t7}	$73,267.73	{e1:t7}	$35,417.80	{e1:t7}	$35,417.80
t8	{e4:t8}	$450.93	{e4:t8}	$450.93	{e4:t8}	$450.93
t9	{e2:t9}	$37,124.80	{e2:t9}	$37,124.80	{e2:t9}	$37,124.80
Total Cost	**$159,025.80**		**$121,069.47**		**$121,069.47**	
Gap	**31.35%**		**0.00%**			

The major saving by the CSP approach comes from the different technology selection for $t7$. In GREEDY, the costs of network operation for technologies $e1$ and $e2$ are approximated by rectilinear distance metric and without considerations of empty travel and directionality constraints. Note that $e2$ is AGV, which is considered a typical example of a technology traveling on unidirectional arcs. (It is possible to consider bi-directional AGV; in that case it behaves like $e1$ but with different costs.) The omission of empty travel and the poor distance approximation make GREEDY choose *e*2 over e1 and pay an extra $37,849.93 for *t*7. Also note that we have one multiple-task combination in the CSP solution: combination {*e*4:*t*2,*t*3} results in $106.41 savings. The diagrammatic representation of the CSP solution and enumeration is provided in Figure 5-5.

The major reason for these improvements is that we consider the MTS design problem as an integrated design problem. Approaches that derive from an integrated problem have the chance to explore the potential savings from multiple-task combinations, better routing of empty transport carriers and sharing of fixed network costs. Comparing columns 3 and 5 of Table 5-2, we observe that the underestimate of cost in the GREEDY approach is inconsistent and unreliable. The cost of network operation is usually used for the approximation of vehicle requirements. The operating cost approximated by GREEDY seems to be inadequate for this purpose.

In this comparison, we do not consider the cost of control systems. However, it is not difficult to see that we might achieve more savings by considering the MTS design problem as a whole with the presence of control system costs. Especially when the fixed cost of control systems is significantly higher than the incremental costs, aggregating tasks might be one way to achieve economy of scale.

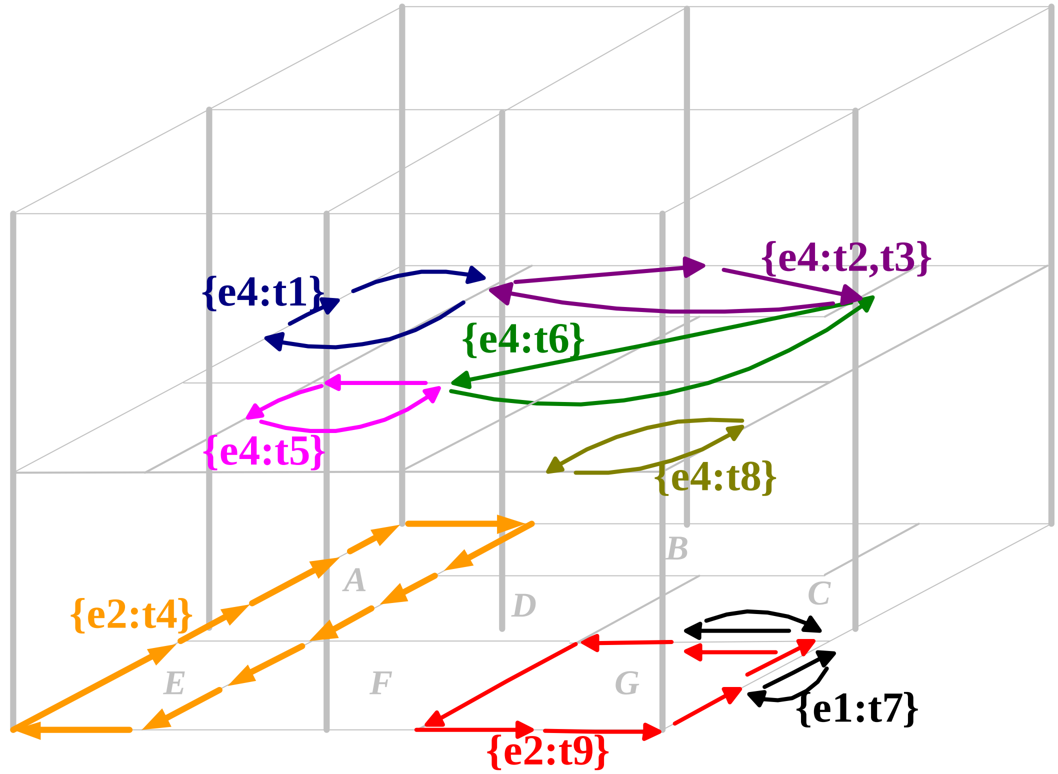

Figure 5-5: MTS Design of Example Problem by the CSP Approach and Enumeration

5.4.2 The CSP Approach versus the CF Approach

In this section, we review the performance and solution quality of two proposed approaches for the integrated MTS design problem. In CHAPTER 4, we propose a compact MILP formulation (CF in short) to approximate the solutions of MTSDP. Although we provide some discussions on the quality of this approximation, the details of the CF approach require more investigations.

The performance and total cost of the example problem by enumeration, CSP and CF are summarized in Table 5-5. Compared to the results by enumeration (240 seconds), the CSP approach (81.13 seconds) requires only 33.85% of the time spent in computation but has a solution cost that is greater by 0.12%. As mentioned in Section 4.4.3, the total cost of the CF approach provides an underestimation of empty travel, and inn this case the objective value is 0.17% lower than the optimal solution. Column CF (adjusted) records the cost of CF task-technology assignments and CSP flow network designs. The total cost of CF (adjusted) is 0.13% greater than the optimal solution.

For solutions provided by the CF approach, there are some differences between the original flow network design and the CSP flow network designs based on task-technology assignments of the CF approach. The diagrammatic representations of solutions by the original CF approach and the CF (adjusted) approach are provided in Figure 5-6 and Figure 5-7, respectively. In terms of flow network structures, the only difference between these two solutions is the design for sub-system {e4: t1,t2,t3}. However, the details of network activity cannot be observed without further analysis. The single-task technology assignments always follow Kuhn's empty travel representation in the CF solution. Thus, we only need to focus on the two multiple-task technology assignments, {e4: t1,t2,t3} and {e4: t6,t8}.

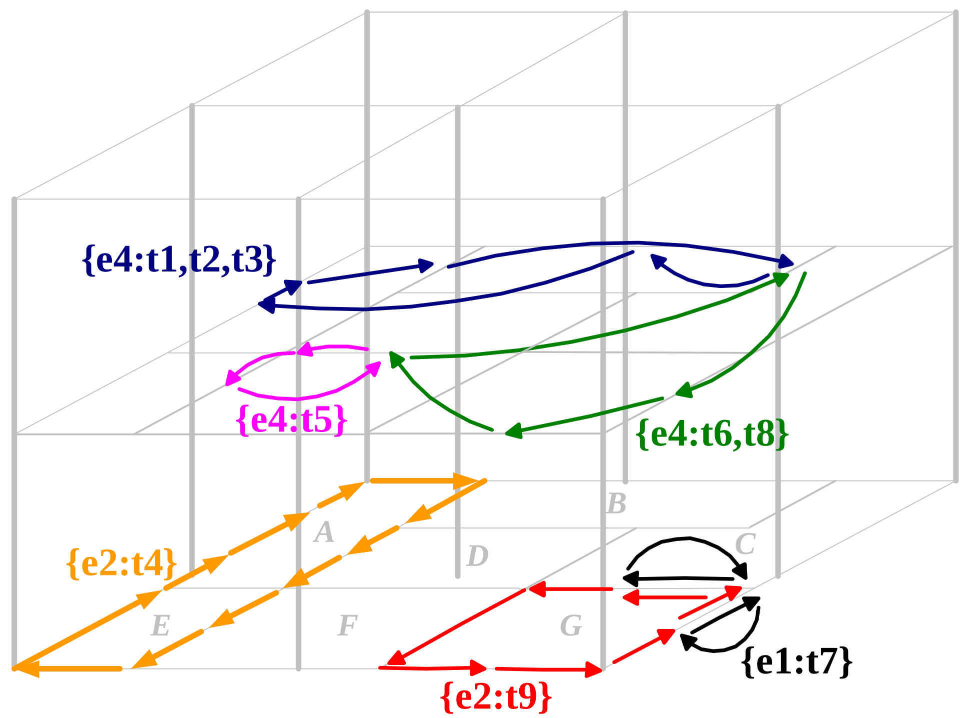

Figure 5-6: MTS Design of Example Problem by the CF Approach

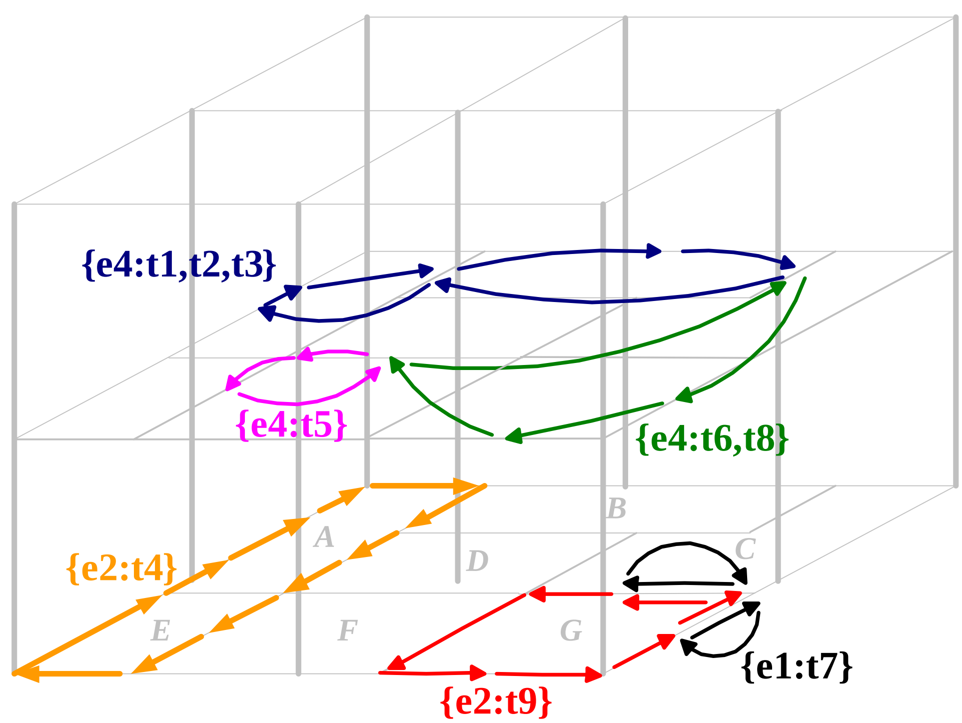

Figure 5-7: MTS Design of Example Problem by the CF (adjusted) Approach

Table 5-5: Performance and Solutions of enumeration, CSP and CF

1	2	3	4
	Enumeration	CSP	CF (Adjusted)
Total Cost	$122,469	$122,621	$122,261 ($122,627)
Difference from Optimal Solution		0.12%	-0.17% (0.13%)

The flow networks of two multiple-task sub-systems by CF and CF (adjusted) are provided in Figure 5-8. Figure 5-8 (a) shows the flow network design of sub-system {e4:t1,t2,t3} by the CF approach. The thick solid arrows indicate the origins and destinations of tasks in this sub-system. The arcs of the flow network are shown by black thin arrows along with their distances. Figure 5-8(b) shows the flow network design of sub-system {e4:t1,t2,t3} by the CF (adjusted) approach. Figure 5-8(c) and (d) show the flow network designs of sub-system {e4:t6,t8} by CF and CF (adjusted), respectively.

The network activities of sub-system {e4:t1,t2,t3} by the CF approach are summarized in Table 5-6. The loaded travel rows record the arcs used by each of three tasks and loaded flow quantity on each arc, measured by unit carrier. For example, task t1 is serviced through arc (0,1) with a flow 120 unit carriers. The empty travel rows record the arcs and the flows of nine different empty travels. For example, there are 20.57 empty carriers traveling from the destination of t1 to the source of t1 along the flow path (1,2), (2,4), (4,3), and (3,0). The total flow on each arc is summarized in the last row of Table 5-6. The last two columns of Table 5-6 present the empty travel ratio and Kuhn's empty travel ratio given the loaded travel requirements of t1, t2 and t3. The empty travel ratio is calculated by the empty travel divided by the loaded travel. Take empty travel from *d*(t1) to *o*(t1) for example: the empty travel ratio, 0.17, is obtained by 20.5714 divided by 120. Similar network activity breakdown for sub-system {e4:t6,t8} by the CF approach is shown in Table 5-7

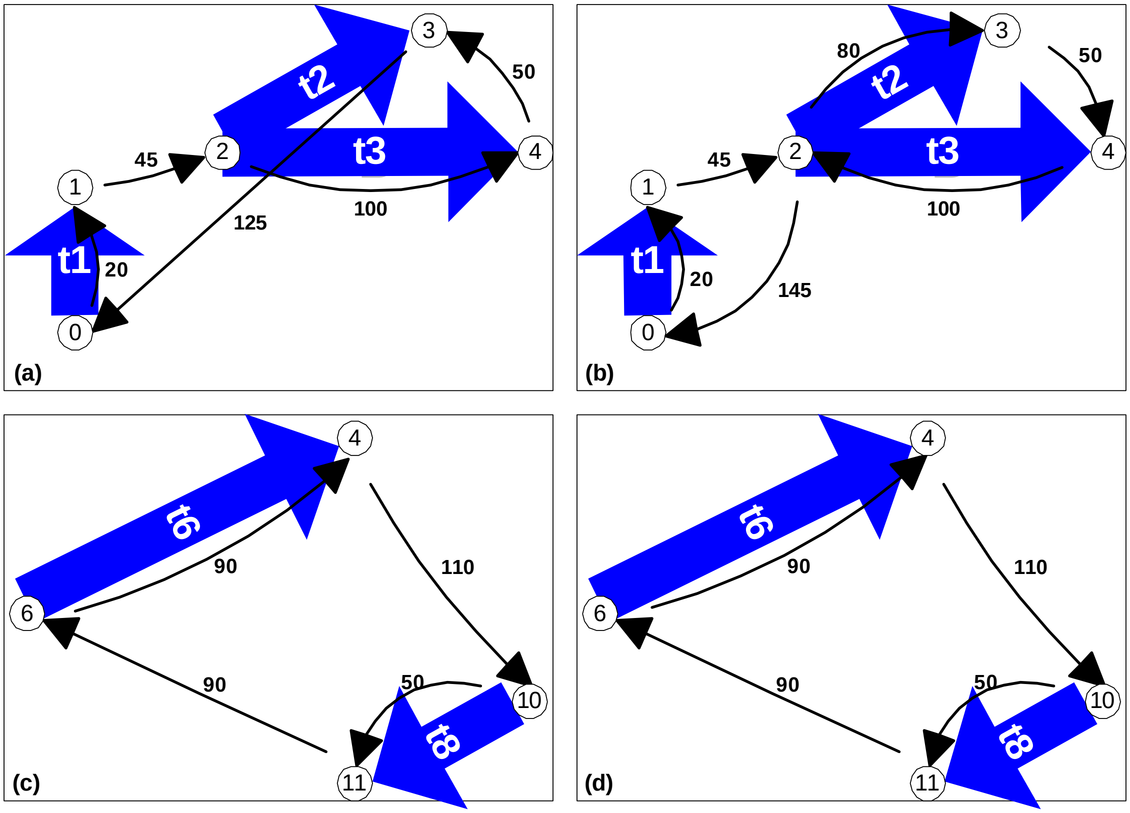

Figure 5-8: Sub-Systems {e4:t1,t2,t3} and {e4:t6,t8} of CF and CF (adjusted)

From the differences of empty travel ratios and Kuhn's empty travel ratios in Table 5-6 and Table 5-7, we can confirm the cause of underestimation by the CF approach is the violation of Kuhn's empty travel ratio. Based on the cost information provided in Section 4.5, the cost for sub-systems {e4:t1,t2,t3} and {e4:t6,t8} is \$2076 each. Following Kuhn's empty travel representation, the costs for sub-systems {e4:t1,t2,t3} and {e4:t6,t8} are \$2258 and \$2,260, respectively.

The task-technology assignments and costs of three solutions for the example problem are provided in Table 5-8. The diagrammatic representations of the designs by CSP and enumeration are shown in Figure 5-9 and Figure 5-10, respectively. Comparing the task-technology assignments and flow network designs of these three approaches, we observe that the linear approximation of the CF approach affects the amount of empty travel and, therefore clustering decisions and, flow network designs.

Table 5-6: Network Activity Breakdown of Sub-system {e4:t1,t2,t3} by CF

	Task		Arc					Empty Travel Ratio	Kuhn's Empty Travel Ratio
			(0,1)	(1,2)	(2,4)	(4,3)	(3,0)		
Loaded Travel	t1		120						
	t2				90	90			
	t3				90				
Empty Travel	t1	t1		20.57	20.57	20.57	20.57	0.17	0.4
	t1	t2		66.86				0.56	0.3
	t1	t3		32.57				0.27	0.3
	t2	t1					66.86	0.74	0.4
	t2	t2	11.57	11.57			11.57	0.13	0.3
	t2	t3	11.57	11.57			11.57	0.13	0.3
	t3	t1				32.57	32.57	0.36	0.4
	t3	t2	11.57	11.57		11.57	11.57	0.13	0.3
	t3	t3	45.86	45.86		45.86	45.86	0.51	0.3
Total			200.57	200.57	200.57	200.57	200.57	3	3

Table 5-7: Network Activity Breakdown of Sub-system {e4:t6,t8} by CF

	Task		Arc				Empty Travel Ratio	Kuhn's Empty Travel Ratio
			(4,10)	(10,11)	(11,6)	(6,4)		
Loaded Travel	t6					180		
	t8			120				
Empty Travel	t6	t6	80.57	80.57	80.57		0.45	0.6
	t6	t8	99.43				0.55	0.4
	t8	t6			99.43		0.83	0.6
	t8	t8	20.57		20.57	20.57	0.17	0.4
Total			200.57	200.57	200.57	200.57	2	2

Table 5-8: Task-Technology Assignments and Costs of Three Solutions

1	2		3		4	
	CF		Enumeration		CSP	
	CLUSTER	COST	CLUSTER	COST	CLUSTER	COST
t1	{e4:t1,t2,t3}	$2,076	{e4:t1,t2}	$1,424	{e4:t1}	$947
t2	{e4:t1,t2,t3}		{e4:t1,t2}		{e4:t2,t3,t6,t8}	$3,563
t3	{e4:t1,t2,t3}		{e4:t3,t6,t8}	$2,936	{e4:t2,t3,t6,t8}	
t4	{e2:t4}	$45,238	{e2:t4}	$45,238	{e2:t4}	$45,238
t5	{e4:t5}	$329	{e4:t5}	$329	{e4:t5}	$329
t6	{e4:t6,t8}	$2,076	{e4:t3,t6,t8}		{e4:t2,t3,t6,t8}	
t7	{e1:t7}	$35,418	{e1:t7}	$35,418	{e1:t7}	$35,418
t8	{e4:t6,t8}		{e4:t3,t6,t8}		{e4:t2,t3,t6,t8}	
t9	{e2:t9}	$37,125	{e2:t9}	$37,125	{e2:t9}	$37,125
Total Cost	**$122,261**		**$122,470**		**$122,621**	

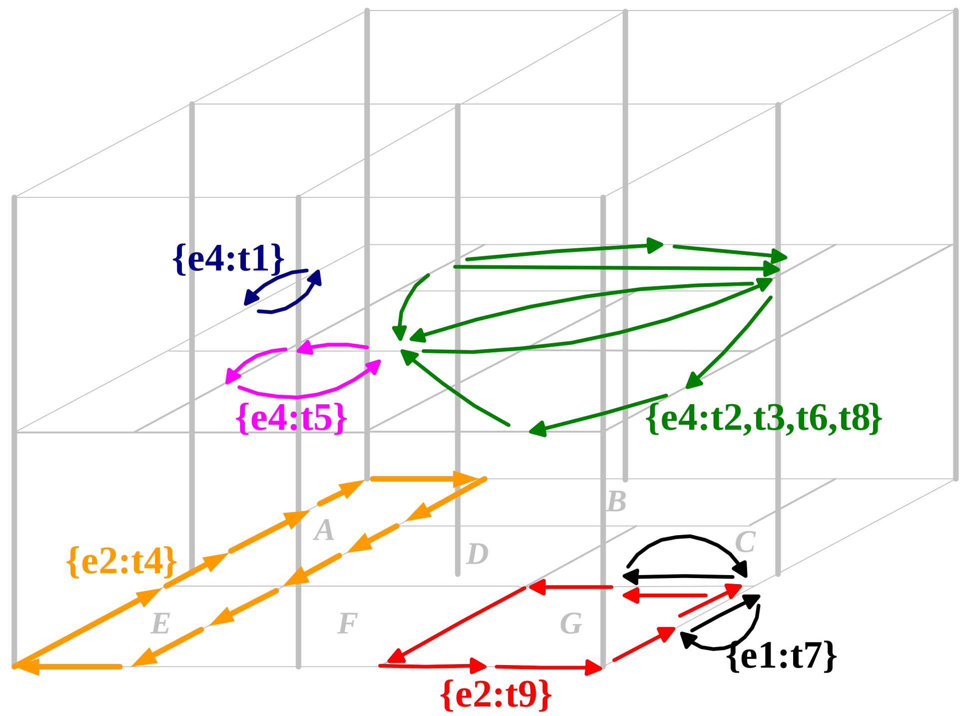

Figure 5-9: MTS Design of Example Problem by the CSP Approach

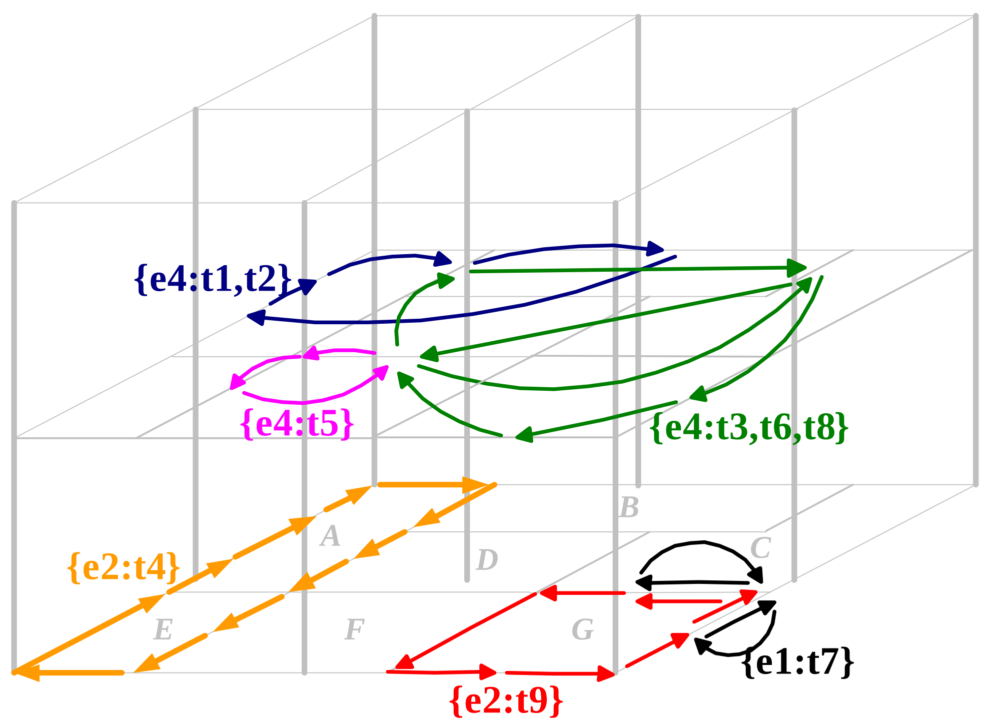

Figure 5-10: MTS Design of Example Problem by Enumeration

5.5 Concluding Remarks

In this chapter, we proposed another solution approach for the integrated MTS design problem in addition to the CF approach presented in CHAPTER 4. This approach, a clustering/set partition approach, decomposes the design process into three phases: task clustering, network connecting and system selection.

For task clustering, we identify the important factors to be used for clustering. We formulate the flow network design problem in a general sense and specify the detailed flow network restrictions for six major transport technology classes. At the last phase, we formulate the system selection problem as a variant of the classic set partition problem to cope with the assignment and resource availability requirements.

We also perform some computational experiments with an illustrative example to compare the performance and solutions of the CSP approach to the solutions of one representative approach in the literature and the CF approach. According to the computational results, we observe that

- Considering the MTS design problem as an integrated problem can make the resulting designs more economical and realistic.
- The objective value provided by the CF approach differs from optimality by a small amount in the illustrative example. However, the results of task clustering and flow network designs could differ from the optimal solution due to the violation of Kuhn's empty travel representation.
- The differences in the solution times of CF and CSP result from the treatments of empty flow. The solutions obtained by the CSP approach follow Kuhn's empty travel ratio by decomposing the MTSDP and embedding empty flows in the flow requirements before solving flow network design problems. On the other hand,

the CF approach is formulated to solve the MTSDP within a lower and an upper bound on Kuhn's empty travel ratio. This can cause the CF approach to violate Kuhn's empty travel ratio and spend more time searching for a lower cost solution by varying the empty travel distributions. This could be one of the reasons we have such a big difference in solution time between the CF and CSP approaches.

CHAPTER 6

CASE PROBLEM: FORD SALINE PLANT

In this chapter we apply one of the proposed approaches, Clustering/Set Partition (CSP) approach, for a material transport system design problem at the FORD Saline Plant. The Saline Plant is a motor parts manufacturing facility of one of the largest automotive companies in the world. A large percentage of the instrument panels and the instrument clusters used in FORD cars and trucks are manufactured at the Saline Plant. The purposes of this chapter are not only to demonstrate material transport system (MTS) designs in a real-world application by the proposed CSP approach but also to show how to compile raw data into appropriate format of the proposed approach.

The CSP approach is based on a decomposition of the material transport system design problem (MTSDP) into clustering, connecting, and system selection phases. The clustering phase is solved by a set of statistical clustering procedures with some crucial factors of transportation requests. The connecting phase leads to variations of flow network design problems, and the system selection phase leads to a set partition problem. For both the connecting and system selection phases, we solve optimization problems with a commercial solver. For details about the CSP approach, please refer to CHAPTER 5.

This chapter is organized in four sections in addition to the introduction. Section 6.1 describes the facility layout, material flow of products, and the production volumes of the Saline Plant. To apply the CSP approach on MTSDP of the Saline Plant, we need to have information about transportation requests, material transport technologies and their working networks. The compilation of these essential data from source data of the Saline Plant are reported in Section 6.2. Computational results and validations of the CSP approach for the Saline Plant are discussed in Section 6.3, and Section 6.4 concludes this chapter.

6.1 Information of the Saline Plant

In this section, we present information for the MTSDP in the Saline Plant. The facility layout and related information is provided in Section 6.1.1. The material flow of four major products and their production volumes are introduced in Section 6.1.2. The data reported in this section is adopted from Material Handling Modernization Program (1985).

6.1.1 Facility Layout

The total floor space of the Saline Plant is approximately 1,640,000 square feet. The warehousing operation for the plant occupies nearly 500,000 square feet or roughly 30% of the total plant floor space. The facility layout of the Saline Plant is shown in Figure 6-1. The rectangular boxes represent the intersections, and the circles represent the input or/and output points of a workstation.

Three warehouses, the east (EWH), west (WWH), and purchased parts warehouse (PWH) are used for the storage of parts and materials. The molding processes of instrument panel are done at workstations 271, 272, and 273. Workstations 293, 294, and 295 are dedicated for the foaming processes. The chrome plating and E-cure are done at workstations 291 and 286, respectively. Workstations 289 and 292 are in charge of finish decorating. The gages and speedometers are assembled at workstation 264, the panel processing is done at workstation 262/294, and sonic welding is done at workstation 281.

The instrument clusters are assembled at workstation 261, and the service pack is stored at workstation 263.

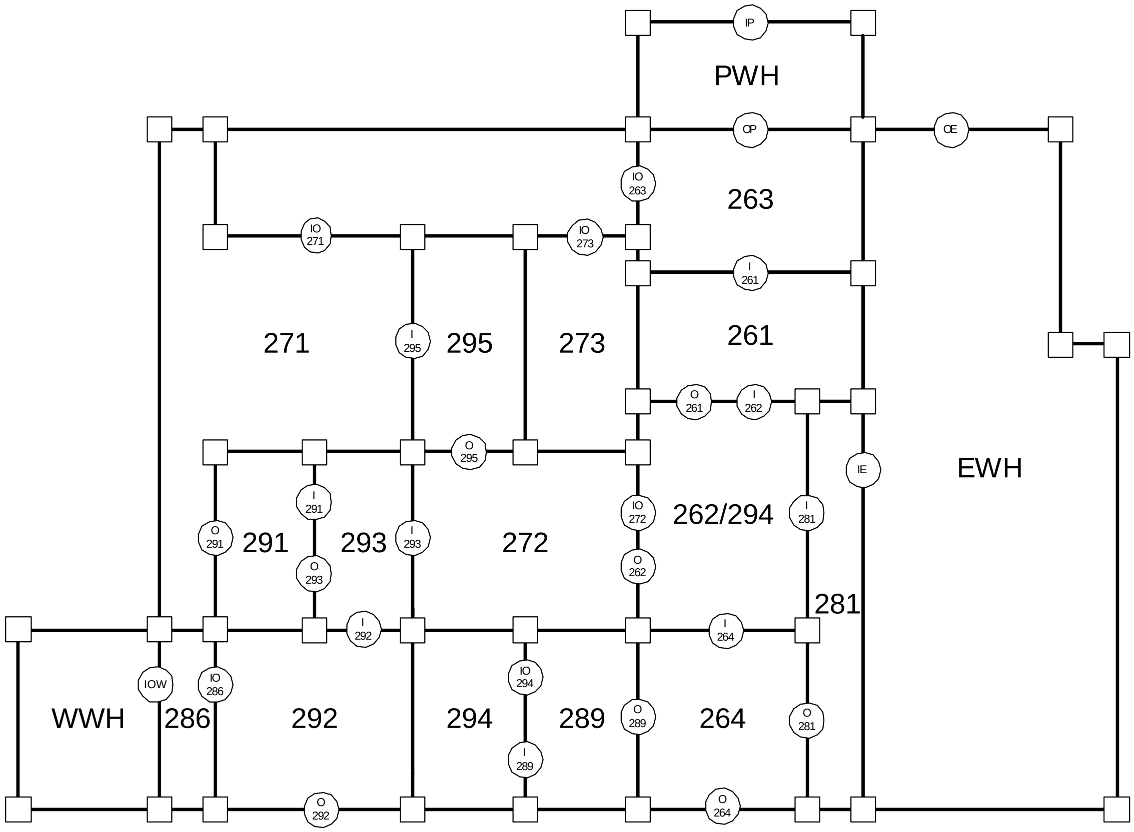

Figure 6-1: Facility Layout of the Saline Plant

6.1.2 Production Volume and Product Material Flows

In this case problem, we consider four major products at the Saline Plant, soft instrument panel, hard instrument panel, instrument cluster assembly, and chrome plated grille. The quarterly production volume of the Saline Plant is summarized in Table 6-1.

Table 6-1: Quarterly Production Volume of the Saline Plant

Product	Production Volume
Soft Instrument Panel	1,524,000 units
Hard Instrument Panel	1,859,000 units
Instrument Cluster Assembly	3,901,000 units
Chrome Plated Grille	2,425,000 units

To better understand the material movement at the Saline Plant, the following material flow diagrams give flow patterns of the products. Figure 6-2 shows the material flow of soft instrument panel. The numbers in the circles are workstation numbers. The material flow of hard instrument panel, instrument cluster assembly, and chrome plated grille are shown in Figure 6-3, Figure 6-4, and Figure 6-5, respectively.

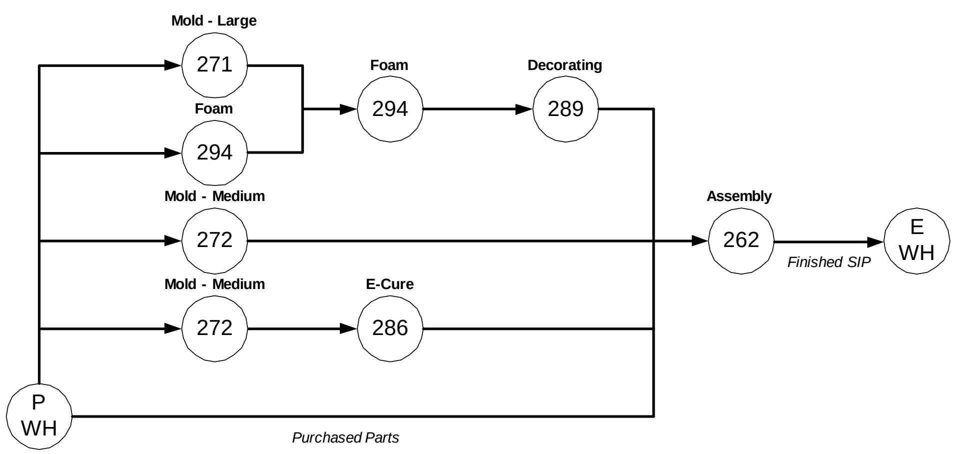

Figure 6-2: Material Flow of Soft Instrument Panel

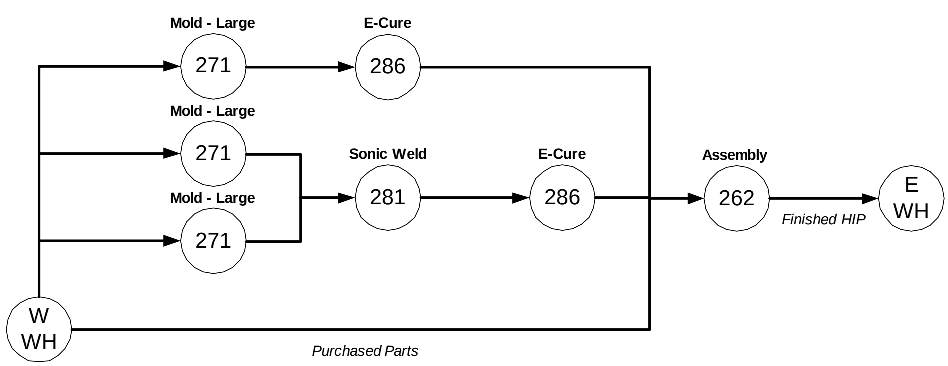

Figure 6-3: Material Flow of Hard Instrument Panel

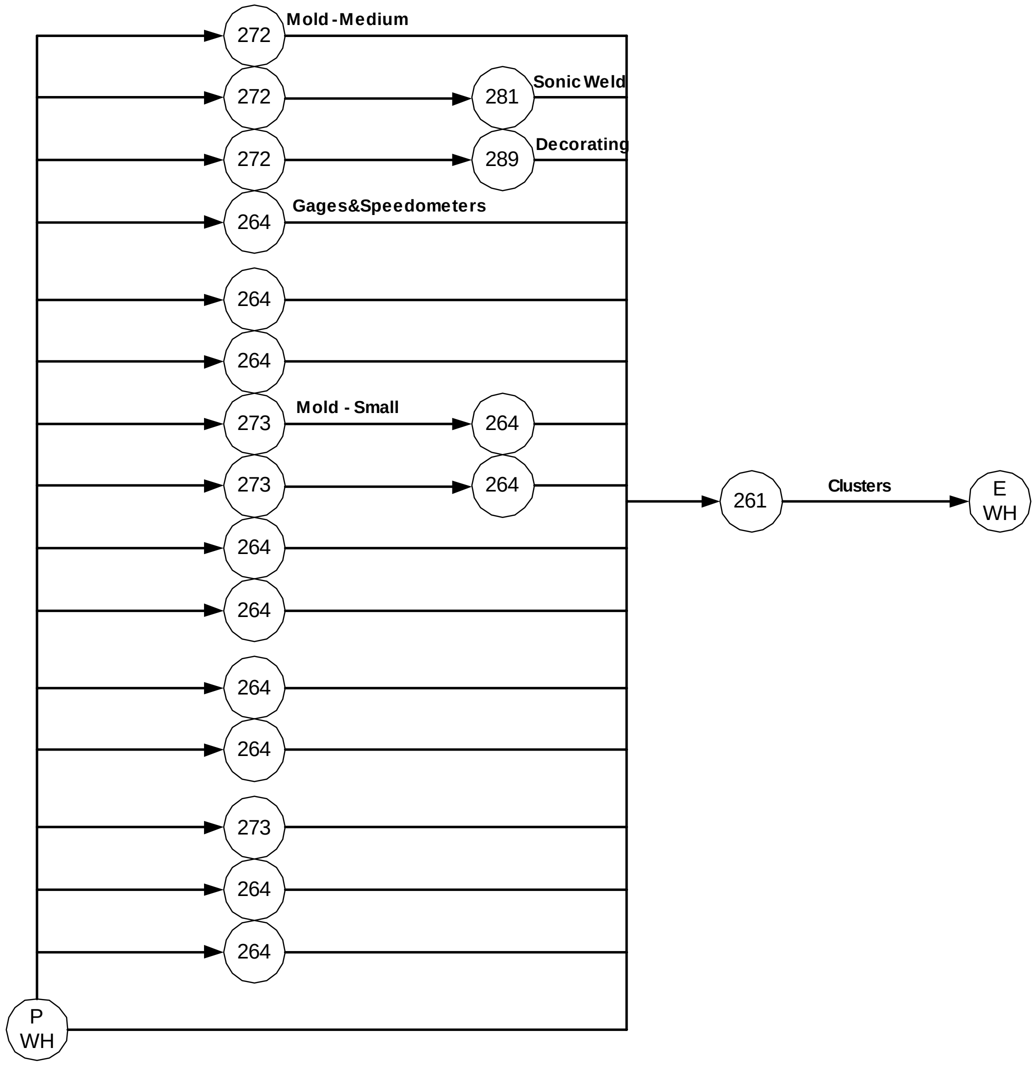

Figure 6-4: Material Flow of Instrument Cluster Assembly

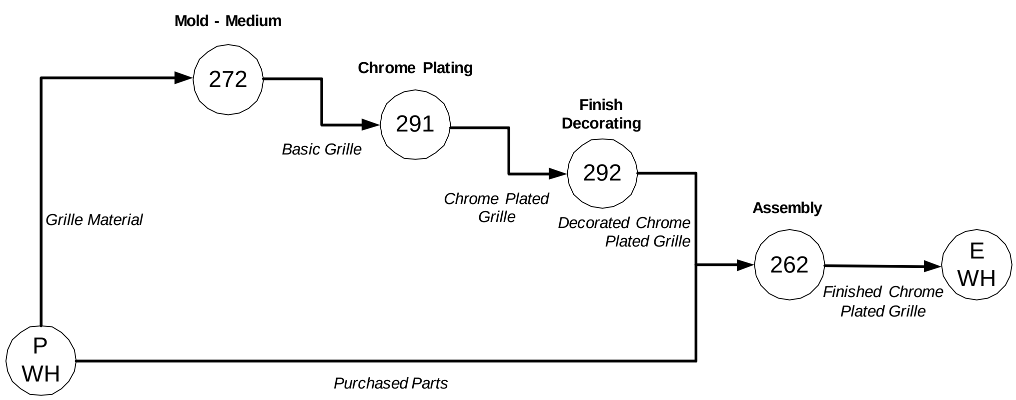

Figure 6-5: Material Flow of Chrome Plated Grille

6.2 Data Preparation for the CSP Approach

In this section, we explain how the raw data of the Saline Plant are compiled into appropriate formats of the proposed MTS design approaches. Although we only apply the CSP approach on the MTSDP of the Saline Plant, the same data preparation procedures can be applied to the other proposed approach. Three types of information are required for the design of a general material transport system by the proposed approaches: technology, working networks, and transportation tasks. The following subsections address each type of information for the Saline Plant.

6.2.1 Information about Technology Candidates

After knowing the requirements of the Saline Plant and other related information, we proposed four technology candidates for its material transport system. The first one is a sit-down counterbalanced lift truck. According to our technology classification introduced in Section 3.3.6, it is an instance of manually driven vehicle, and we will refer this technology as MDV. The second technology candidate is a unit-load AGV. It is an instance of automatic guided vehicle, and we will refer to it as AGV. The third technology candidate is a powered roller conveyor. It is an instance of floor support conveyor, and we will refer to it as FSC. The fourth technology candidate is a trolley conveyor. It is an instance of overhead trolley conveyor, and we will refer to it as OTC.

The focus of this subsection is to set up the cost information of each technology candidate according to the proposed cost models (For details of cost models, please refer to Appendix A). In this research, we consider the lifetime cost of material transport system by including network operating cost, network construction cost and control system cost. The life span of a material transport system is assumed to be five years; the

Saline Plant operates 300 days per year and 7 hours per day. Table 6-2 provides the operating speed of each technology candidates.

Table 6-2: Speed Information of Technology Candidates

	MDV	AGV	FSC	OTC
Speed	7 mph	3 mph	1 mph	1 mph

The detailed cost items and figures of network operating cost, network construction cost and control system cost are provided in Table 6-3, Table 6-4 and Table 6-5, respectively. Network operating cost is used to measure the costs incurred by network activity per linear foot. In Table 6-3: row (1) gives the estimates of unit carrier cost for each technology candidate, row (2) gives the amortized unit carriers cost on a working day basis, row (3) gives the daily driver wage, row (4) gives the daily power consumptions of loaded travel, row (5) gives the daily maintenance expenses, row (6) gives the daily power consumptions of empty travel, and row (7) gives the daily total network operating cost.

Table 6-3: Network Operating Cost Information of Technology Candidates

Row Number	Cost Item	MDV	AGV	FSC	OTC
(1)	Unit Carrier	$30,000	$75,000		$100
(2)	Unit Carrier (daily)	$20	$50		$0.07
(3)	Driver (daily)	$250			
(4)	Power (daily)	$25	$25	$0.35	$0.20
(5)	Maintenance (daily)	$20	$40		$0.15
(6)	Power Empty (daily)			$0.15	
(7)	Total (daily)	$315	$115	$0.50	$0.42

The network construction cost relates to the fixed portion of material transport network per linear foot. In Table 6-4: row (1) gives the estimates of guide path/ support per foot for each technology candidate, row (2) gives the amortized unit guide path/ support cost on a working day basis, row (3) gives the daily space cost per foot, row (4) gives the daily maintenance expenses per foot, row (5) gives the daily connection cost per foot, and row (6) gives the daily total network construction cost per foot.

Table 6-4: Network Construction Cost Information of Technology Candidates

Row Number	Cost Item	MDV	AGV	FSC	OTC
(1)	Guide Path/Support		$200	$1,000	$200
(2)	Guide Path/Support (daily)		$0.13	$0.67	$0.13
(3)	Space (daily)	$0.50	$0.50	$0.50	
(4)	Maintenance (daily)	$0.05	$0.50	$0.50	$1.50
(5)	Connection (daily)		$3.33		$0.50
(6)	Total (daily)	$0.55	$4.46	$1.67	$2.13

As mentioned in Section 4.1, we modeled control system cost into two parts: fixed cost and incremental cost associated with the number of tasks handled in a (sub) system. In Table 6-5: row (1) gives the estimates of the fixed portion of control system for each technology candidate, row (2) gives the amortized fixed cost of control system on a working day basis, row (3) gives the estimates of incremental portion of control system, and row (4) gives the amortized incremental cost of control system on a working day basis.

Table 6-5: Control System Cost Information of Technology Candidates

Row Number	Cost Item	MDV	AGV	FSC	OTC
(1)	Fixed Cost	$20,000	$100,000	$10,000	$50,000
(2)	Fixed Cost (daily)	$13.33	$66.67	$6.67	$33.33
(3)	Incremental Cost	$10,000	$20,000		$20,000
(4)	Incremental Cost (daily)	$6.67	$13.33		$13.33

The cost figures provided in Table 6-3, Table 6-4 and Table 6-5 are used as essential input information for the proposed approaches based on a set of general and technology class dependent cost formulations provided in Appendix A.

6.2.2 Information about Working Networks

Another important input information for the proposed MTS design approaches is the working network of each technology candidate. According to the layout information provided by the Saline Plant, we partitioned the floor plan by grid modules of size 40 ft by 60 ft as shown in Figure 6-6. Take WWH for example, it is a 60,000 square feet area with width 200 feet and length 300 feet, represented by (200/40)×(300/60) = 5×5 = 25 grid modules.

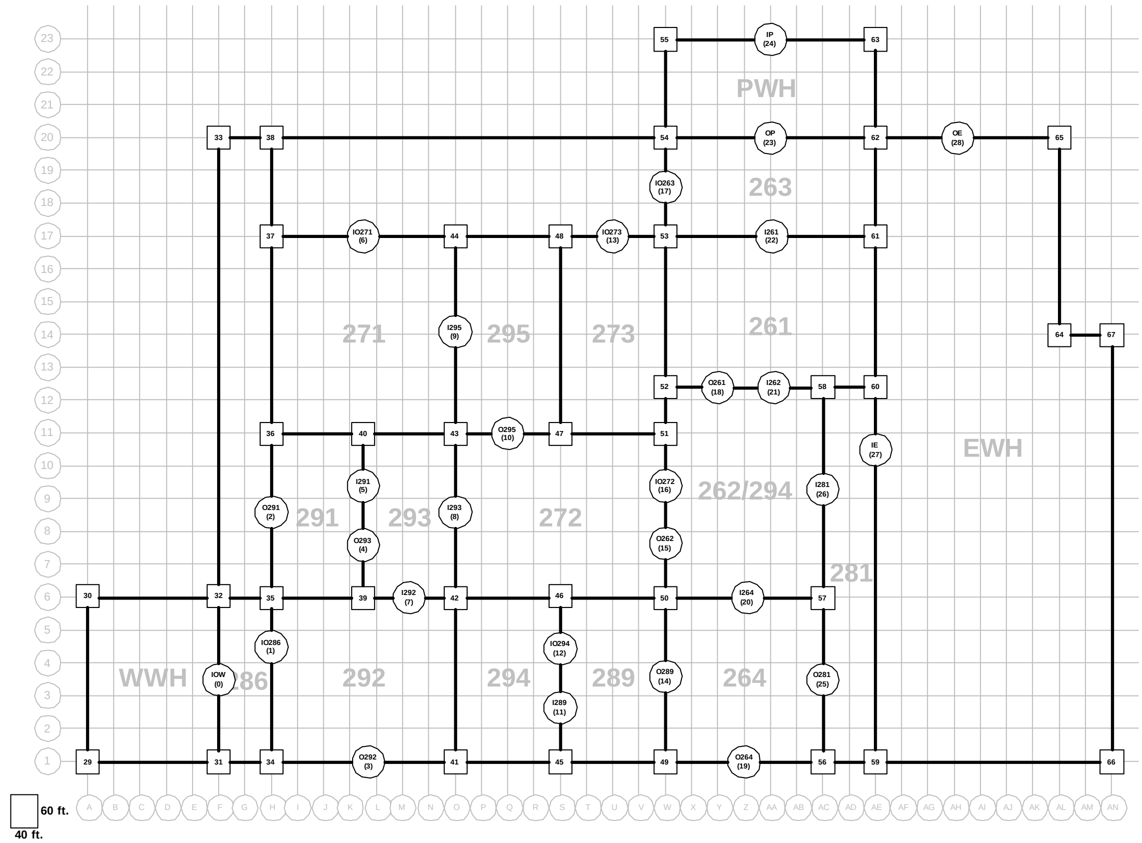

Figure 6-6: Revised Facility Layout of the Saline Plant

The working networks of four technology candidates are prepared by aforementioned methods (see Section 3.3.2 for details). The arc distances of each working network are approximated based on the revised facility layout of the Saline Plant in Figure 6-6. Network operating cost and network construction cost are applied to each arc of each working network based on the distance and costs according to the cost formulations provided in Appendix A.

The availability restrictions on space and flow path crossing constraints require us to develop the working networks. Among the transport technologies considered in this case problem, flow path crossings of conveyor system are common in MTS design. The installation of a floor level conveyor blocks the flow of vehicle-based technologies once the aisle path is crossed unless some expensive remedies take place, e.g., elevating devices. In order to prevent such designs, we need to characterize these flow path crossings in the working networks. A network transformation is provided as follows:

- Shrinking every edge of workstation boundaries into a node. Note that *shrinking* an edge means deleting an edge and collapsing its two endpoints.
- Connecting the shrunken edge nodes belonged to the same workstation by a pair of opposite directed arcs between every pair of edge nodes.
- Connecting the origin/destination node of every task to every edge node belonging to the origin/destination workstation by a pair of opposite directed arcs between every pair of origin/destination node and edge node.

Figure 6-7 gives an example of conveyor network transformation. In this example, there are three workstations and three tasks as shown in Figure 6-7(a). Figure 6-7(b) demonstrates the shrinking process applied on the example. Shrunken edge nodes are represented by black solid circles with white numerals. Figure 6-7(c) shows the connecting of pairs of edge nodes within the same workstation with a pair of opposite directed arcs (for clarity of illustration, bi-directional single arcs are used). As shown in Figure 6-7(d), the connections between the origin/destination node of every task and workstation are obtained by connecting a pair of opposite directed arcs (again, bi-directional single arcs are used) from origin/destination node to the edge nodes of the same workstations, respectively.

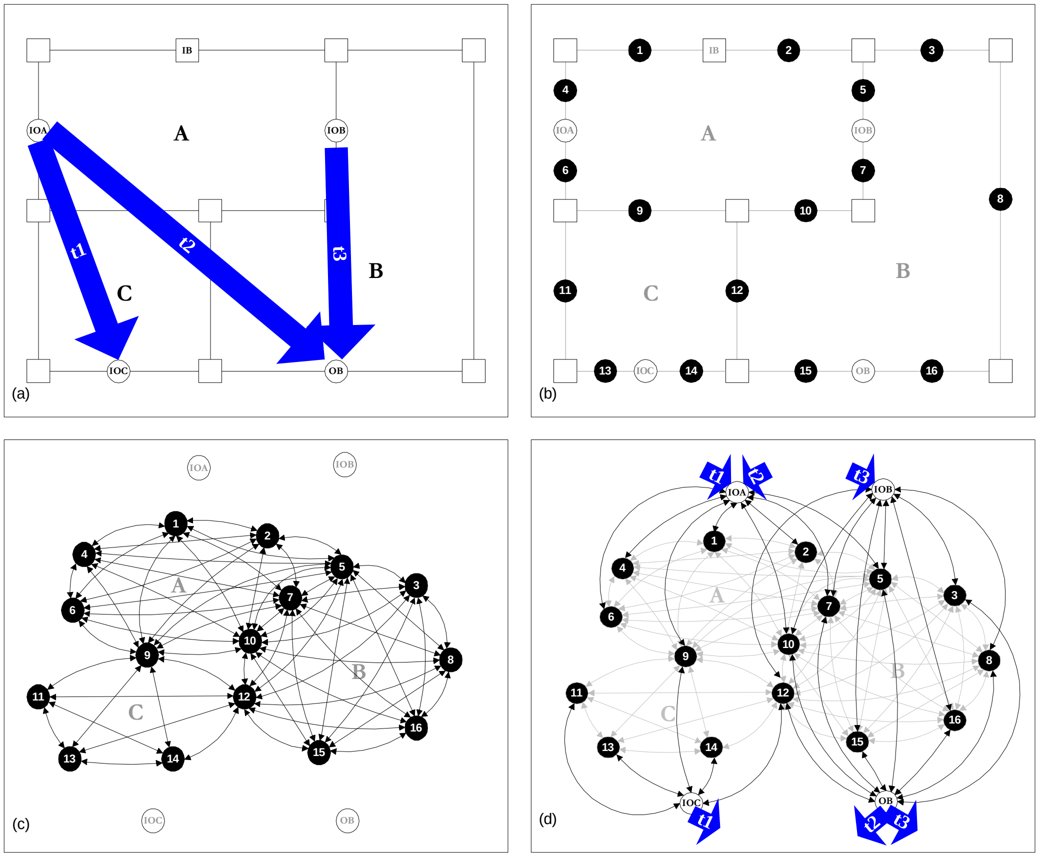

Figure 6-7: Conveyor Network Transformation of an Example

The arc capacity of each working network is determined by the product of ideal daily capacity and a utilization factor. The ideal daily capacity is obtained by daily total travel distance at operating speed divided by length of unit technology. The length of unit technology includes the space of physical equipment and required clearance. The utilization factor reflects operational delays, e.g., waiting for pickup or delivery. The lengths of unit technology and utilization factors used in this case problem are summarized in Table 6-6.

Table 6-6: Length of Technology and Utilization Factor of Technology Candidate

	MDV	AGV	FSC	OTC
Length of Unit Technology	100 ft	50 ft	15 ft	6 ft
Utilization Factor	80%	80%	70%	70%

6.2.3 *Information about Transportation Tasks*

The transportation tasks of this case problem for the Saline Plant are compiled from the material flows and production volumes of four major products given in Section 6.1. We summarize the transportation requests by material, origin, and destination in Table 6-7. The transportation requirements, denoted in unit-load carriers, are estimated by converting quarterly production volumes into seven-hour time buckets (length of a working day).

Table 6-8, Table 6-9, and Table 6-10 summarize the same information (material, from/to workstation, and unit carrier requirements of four technology candidates) of transportation tasks of hard instrument panel, instrument cluster assembly, and chrome plated grille, respectively.

After the aggregation of tasks with the same product and the same from/to workstations; we obtain Table 6-11. Note that the bold font of an entry for task and technology in Table 6-11 indicates that the technology is not able to handle the corresponding task because the transportation requirement exceeds arc capacity constraints. The arc capacities of four working networks associated with each technology candidate are provided in Table 6-12.

Table 6-7: Task Information of Typical Soft Instrument Panel

Task No.	Material	From	To	Transportation Requirement (Unit-load Carrier)			
				MDV	AGV	FSC	OTC
1	SUBSTRATE	PWH	271	678	339	6774	6774
2	VINYL SKIN	PWH	294	678	339	6774	6774
3	GLV COMPT.	PWH	272	81	41	2033	339
4	GLV COMPT. Dr.	PWH	272	22	11	339	85
5	PARTS	PWH	262	136	68	2033	565
6	SUBSTRATE	271	294	678	339	6774	6774
7	PARTS	272	286	136	68	2033	565
8	SUBSTRATE	294	289	678	339	6774	6774
9	GLV COMPT. Dr.	286	262	22	11	339	85
10	SUBSTRATE	289	262	678	339	6774	6774
11	INST. PNL ASS’Y	262	EWH	678	339	6774	6774

Table 6-8: Task Information of Typical Hard Instrument Panel

Task No.	Material	From	To	Transportation Requirement (Unit-load Carrier)			
				MDV	AGV	FSC	OTC
1	SUBSTRATE	PWH	271	1033	517	8263	8263
2	GLV COMPT.	PWH	272	138	69	2479	551
3	GLV BOX ASS'Y	PWH	272	35	18	414	138
4	HARNESS RETD	PWH	273	35	18	414	138
5	PARTS	PWH	262	218	109	2479	919
6	SUBSTRATE	271	286	1033	517	8263	8263
7	GLV COMPT.	272	281	138	69	2479	551
8	GLV BOX ASS'Y	272	281	35	18	414	138
9	GB REINF	281	286	166	83	2893	689
10	GB REINF	286	262	166	83	2893	689
11	SUBSTRATE	286	262	1033	517	8263	8263
12	HARNESS RETD	273	262	35	18	414	138
13	INST. PNL ASS'Y	262	EWH	1033	517	8263	8263

Table 6-9: Task Information of Typical Instrument Cluster Assembly

Task No.	Material	From	To	Transportation Requirement (Unit-load Carrier)			
				MDV	AGV	FSC	OTC
1	BACK PLATE	PWH	272	73	37	867	289
2	INST CLS LENS	PWH	272	25	13	867	97
3	MASK	PWH	272	25	13	867	97
4	SPEEDO DIAL	PWH	273	25	13	434	97
5	ODOM ROLLS	PWH	273	25	13	434	97
6	BLUE FILTER	PWH	273	25	13	434	97
7	SPEEDO MAG	PWH	264	25	13	434	97
8	SPEEDO FRAME	PWH	264	25	13	434	97
9	SPEEDO CUP	PWH	264	25	13	434	97
10	ODOM PINIONS	PWH	264	13	7	434	49
11	ODOM BRIDGE	PWH	264	13	7	434	49
12	SPEEDO PINTR	PWH	264	25	13	434	97
13	GAGE CU MOLD	PWH	264	49	25	867	193
14	BULB ASS'Y	PWH	264	25	13	434	97
15	VOLTAGE REG	PWH	264	49	25	867	193
16	SPEED ASS'Y	264	261	169	85	867	667
17	GAGE ASS'Y	264	261	73	37	867	289
18	BULB ASS'Y	264	261	25	13	434	97
19	INST CLS LENS	272	281	25	13	867	97
20	MASK	272	289	25	13	867	97
21	INST CLS LENS	281	261	25	13	867	97
22	MASK	289	261	25	13	867	97
23	SPEEDO DIAL	273	264	25	13	434	97
24	PRCHSED PARTS	PWH	261	121	61	1734	482
25	BLUE FILTER	273	261	25	13	434	97
26	INST CLS ASS'Y	261	EWH	362	181	1734	1445

Table 6-10: Task Information of Chrome Plated Grille

Task No.	Material	From	To	Transportation Requirement (Unit-load Carrier)			
				MDV	AGV	FSC	OTC
1	BASE GRILLE	PWH	272	1348	674	10778	10778
2	PARTS	PWH	262	284	142	3234	1198
3	BASE GRILLE	272	291	1348	674	10778	10778
4	BASE GRILLE	291	292	1348	674	10778	10778
5	BASE GRILLE	292	262	1348	674	10778	10778
6	GRILLE ASS'Y	262	EWH	1348	674	10778	10778

Table 6-11: Task Information of the Saline Plant

Task No.	From		To		Transportation Requirement (Unit-load Carrier)			
	Name	No.	Name	No.	MDV	AGV	FSC	OTC
1	PWH	23	261	22	121	61	**1734**	482
2	PWH	23	262	21	638	319	**7746**	2682
3	PWH	23	264	20	249	129	**4772**	969
4	PWH	23	271	6	1711	856	**15037**	**15037**
5	PWH	23	272	16	1747	876	**18644**	**12374**
6	PWH	23	273	13	110	57	1716	429
7	PWH	23	294	12	678	339	**6774**	**6774**
8	261	18	EWH	27	362	181	**1734**	1445
9	262	15	EWH	27	**3059**	1530	**25815**	**25815**
10	264	19	261	22	316	160	**3035**	1246
11	271	6	294	21	678	339	**6774**	**6774**
12	271	6	286	1	1033	517	**8263**	**8263**
13	272	16	286	1	136	68	**2033**	565
14	272	16	289	11	25	13	867	97
15	272	16	291	5	1348	674	**10778**	**10778**
16	272	16	281	26	198	100	**3760**	786
17	273	13	261	22	25	13	434	97
18	273	13	262	21	35	18	414	138
19	273	13	264	20	25	13	434	97
20	281	25	261	22	25	13	867	97
21	281	25	286	1	166	83	**2893**	689
22	286	1	262	21	1221	611	**11495**	**9037**
23	289	14	262	21	678	339	**6774**	**6774**
24	289	14	261	22	25	13	867	97
25	291	2	292	7	1348	674	**10778**	**10778**
26	292	3	262	21	1348	674	**10778**	**10778**
27	294	12	289	11	678	339	**6774**	**6774**

Table 6-12: Arc Capacities of Working Networks

	MDV	AGV	FSC	OTC
Arc Capacity (Unit Technology)	2069	1774	1724	4312

6.3 Material Transport System Designs for the Saline Plant

In this section, we study MTS designs of the proposed CSP approach for the Saline Plant. The basic MTS design of the Saline Plant is presented in Section 6.3.1. We show the impact of flow path crossing on the MTS design in Section 6.3.2. In general, the proposed CSP approach does not guarantee that the resulting MTS design is optimal. In Section 6.3.3, we show the quality of the proposed approach by comparing the results of the CSP approach and enumeration with smaller instances from MTSDP of the Saline Plant. The computations for the enumeration and CSP approaches are done on a PC with 700 MHz Pentium III CPU and 512 MB RAM. The statistical clustering is done by using the clustering analysis of MINITAB 14. We solve all optimization models by using the MIP solver of ILOG CPLEX 8.1.

6.3.1 MTS Design of the Saline Plant

The MTS design for the Saline Plant is done by the proposed CSP approach. For details about this approach, please refer to CHAPTER 5. The CSP approach is a three-phase approach based on the decomposition of general MTS design problems. At the task-clustering phase, we collect 208 task clusters based on the three clustering criteria introduced in Section 5.1. These 208 flow network design problems are solved at the network-connecting phase. The tasks clusters and their costs then become the input information for the system-selection phase.

The task-technology assignments of the MTS design for the Saline Plant is summarized in Table 6-13. There are 18 task clusters chosen to partition 27 tasks. The first column of Table 6-13 denotes the task cluster number; the tasks included, technology assigned, and the corresponding costs are summarized in the second, third, and fourth columns of the table. The total cost of the MTS design at the Saline Plant by the CSP approach is $85,547,663. It took 1048 seconds to solve 208 flow network design problems and 0.24 seconds to solve one set partition problem.

Table 6-13: Task-Technology Assignments of MTS Design for the Saline Plant

Cluster No.	Tasks Included	Technology	Cost
105	4	AGV	$10,322,680
106	5	AGV	$11,139,780
110	9	AGV	$17,269,180
112	11	AGV	$4,763,970
134	22, 26	AGV	$21,828,393
136	14, 27	AGV	$272,188
137	12, 25	AGV	$11,079,493
143	7, 23	AGV	$8,411,343
175	19	FSC	$4,098
177	17, 18	FSC	$4,015
178	1	OTC	$6,432
179	2	OTC	$46,432
181	6	OTC	$6,463
182	8	OTC	$19,126
186	16	OTC	$11,164
196	13, 15	OTC	$250,708
199	3, 21	OTC	$62,395
200	10, 20, 24	OTC	$49,801

Table 6-13 only shows the MTS design for the Saline Plant from the perspective of task-technology assignments. There are some concerns about this design with respect to flow network designs. The flow network design of cluster 106 is shown in Figure 6-8. The assigned technology for cluster 106 is AGV and there is only one task in this cluster, *t*5. Notice that the flow network of cluster 106 uses an arc from node 52 to node 53. This means the aisle between node 52 and node 53 must have the clearance for the AGV system.

The flow network design for another subsystem, cluster 177, is shown in Figure 6-9. Cluster 177 has two tasks, *t*17 and *t*18, and the assigned technology is FSC. As shown in Figure 6-9, this cluster requires a floor-support conveyor system that starts at node 13, travels through workstation 273, cuts across the aisle between node 52 and node 53, splits into two branches inside workstation 261, with one branch ending at node 22 and the other at node 21. These two flow network designs of clusters 106 and 177 leads to the flow path crossing at the aisle between node 52 and node 53.

Other flow path crossings also exist between the flow network designs of cluster 175, 112, 134, and 136 at aisles of node 47 and 51; clusters 175, 106, 110, 136, and 143 at aisles of node 16 and 15; clusters 175, 106 and 136 at aisles of node 50 and 20. The MTS design for the Saline Plant by the CSP approach with the flow path crossing constraints is presented in the next Section.

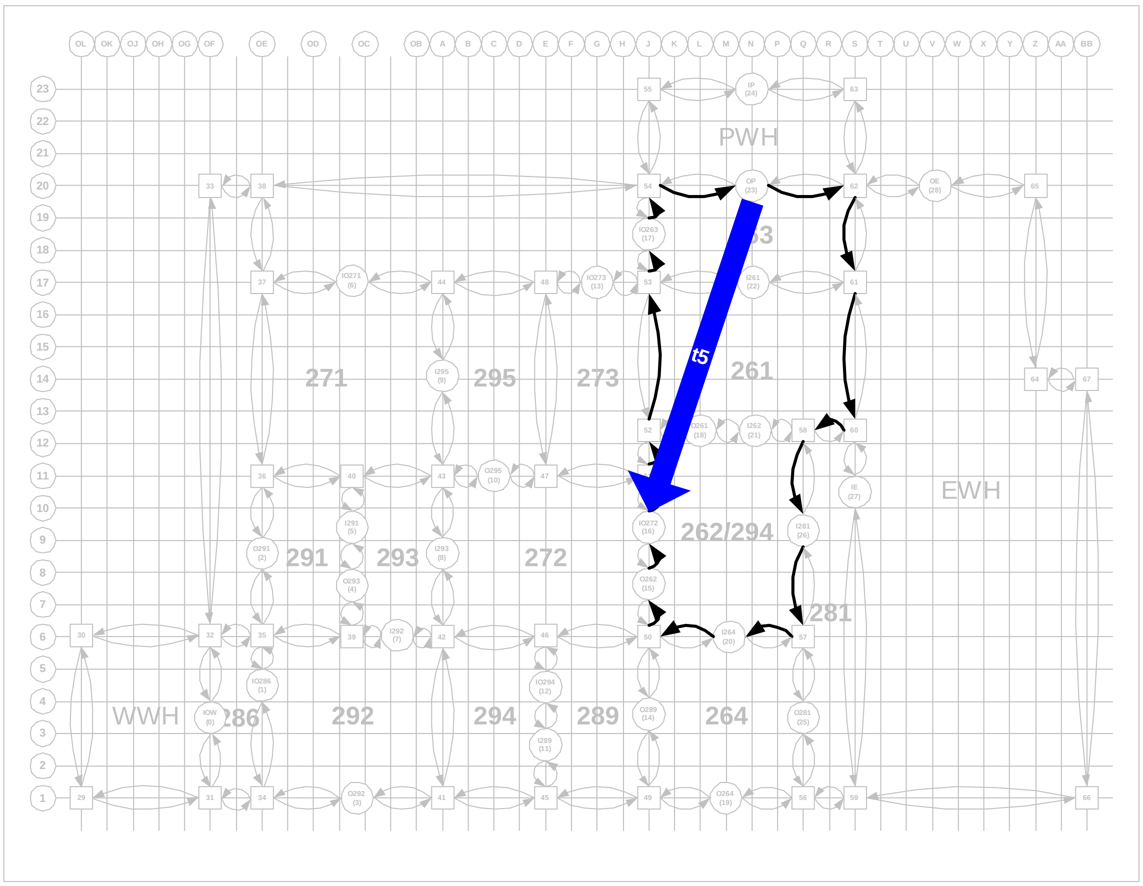

Figure 6-8: Flow Network Design of Cluster 106

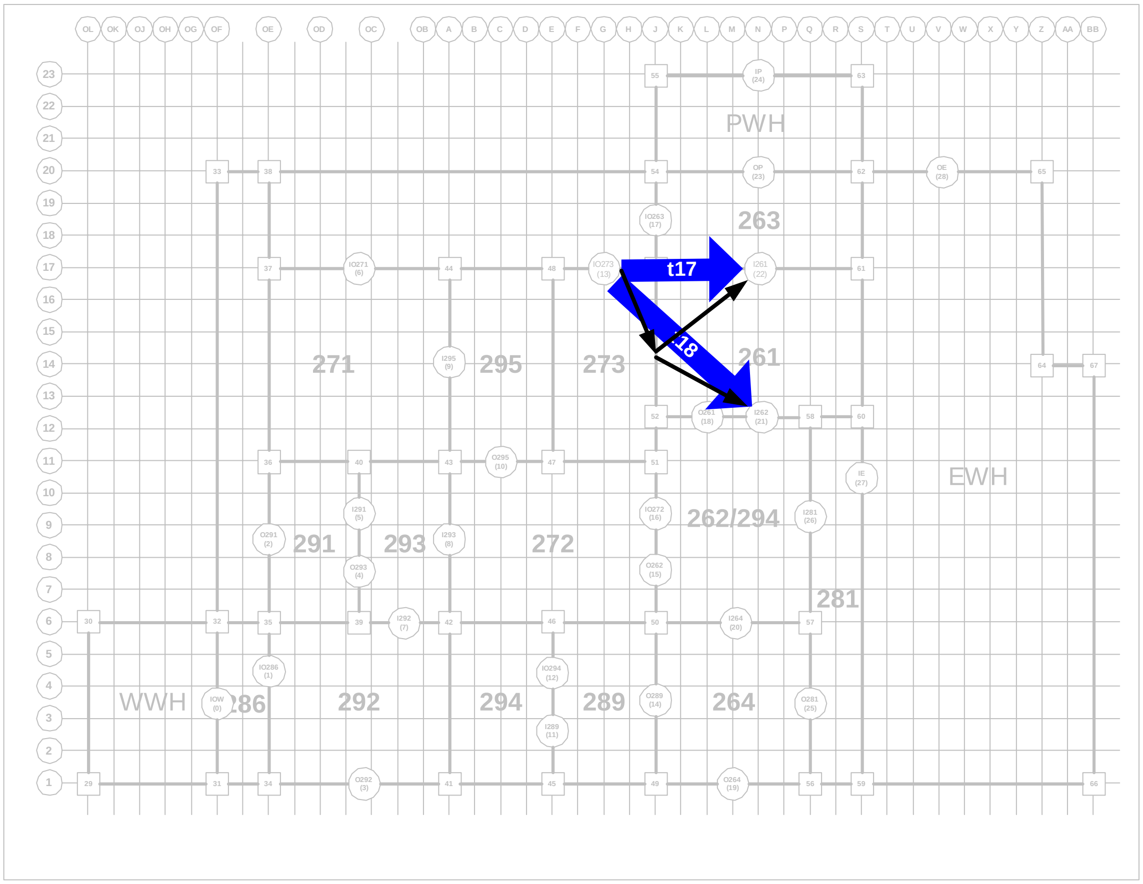

Figure 6-9: Flow Network Design of Cluster 177

6.3.2 MTS Design of the Saline Plant with Flow Path Crossing Constraint

In this section, we present the MTS design with flow path crossing constraints for the Saline Plant under the proposed CSP approach. A modeling technique is introduced in Section 5.3.3, and its corresponding network transformation is illustrated in Section 6.2.2. The same 208 task clusters and their flow network designs from previous section are used. According to the flow network designs, we introduced the flow path crossing constraints in the system-selection phase. The total cost of the MTS design by the CSP approach is $85,548,969. It takes 0.56 seconds to solve this set partition problem.

The task-technology assignments of MTS design with flow path crossing constraints are summarized in Table 6-14. There are 17 task clusters chosen to partition

27 tasks. Compared to the assignments without considering flow path crossing constraints, the new design replaces the tasks assigned to FSC by assigning these tasks to OTC. Clusters 175 and 177 from Table 6-13 no longer exist in the new design. Tasks 17, 18 and 19, associated with clusters 175 and 177, are assigned to OTC with task 20. In Table 6-13, task 20 belongs to the new three-task cluster 204 with tasks 10 and 24. A new cluster 193 includes task 10 and 14.

From the perspective of cost, the difference of MTS designs with and without flow path crossing constraints is $1306. This means we can resolve the undesirable flow path crossings in Section 6.3.1 with a 0.0015% total cost increase.

Table 6-14: Task-Technology Assignments of MTS Design with Flow Path Crossing Constraints for the Saline Plant

Cluster No.	Tasks Included	Technology	Cost
105	4	AGV	$10,322,680
106	5	AGV	$11,139,780
110	9	AGV	$17,269,180
112	11	AGV	$4,763,970
134	22, 26	AGV	$21,828,393
136	14, 27	AGV	$272,188
137	12, 25	AGV	$11,079,493
143	7, 23	AGV	$8,411,343
178	1	OTC	$6,432
179	2	OTC	$46,432
181	6	OTC	$6,463
182	8	OTC	$19,126
186	16	OTC	$11,164
193	10, 24	OTC	$46,682
196	13, 15	OTC	$250,708
199	3, 21	OTC	$62,395
204	17,18,19,20	OTC	$12,539

6.3.3 Validation of the CSP Approach in the Saline Plant

The proposed CSP approach does not guarantee that the MTS design of this approach is optimal. In the task-clustering phase, we only select some promising task clusters from all possible combinations based on our knowledge of MTS design problems. This does make it possible to solve MTS design problems with reasonable size in a reasonable time. However, it does raise questions about the quality of solutions.

In this section, we present experimental results on validating the proposed approach for the MTS design problem at the Saline Plant. We prepare four sets of experiments with six, eight, ten, and twelve tasks, respectively. Each set of experiment has three instances of MTS design problem whose tasks are selected from the 27 tasks of the Saline Plant. Thus, there are a total of 12 instances. The information of technology candidates and working networks remain the same as the full-scale MTS design problem of the Saline Plant.

In these 12 instances, the tasks of 6A (instance A of six-task instances), 8A, 10A, and 12A are selected by tasks sharing the same origins. The tasks of 6B are selected by the tasks sharing the same destinations. The tasks of the remaining instances are selected randomly. For each instance, we solved the MTS design problem by both enumeration and the CSP approach. The results of these experiments are summarized in Table 6-15. For each instance, we record the total cost of both approaches (Enumeration and CSP), the cost differences, and the percentage of cost difference to the total cost of design by enumeration. For each set of 3 experiments, we compute the average percentage of cost difference. For the entire set of 12 experiments, we compute the overall average percentage of cost difference.

The average percentage of cost difference over 12 instances is less than 1%. The individual differences averages of 4 experiment sets are presented in Figure 6-10. The instance with the largest difference, 3.34%, is 6C, and three instances, 6A, 6B, 8C, have the optimal solution by the CSP approach. More importantly, it seems there is no evidence that the difference percentage grows with the increasing of number of tasks.

Table 6-15: Summary of Validation Experiments

Six-Task Instances				
Instance	A	B	C	Average Percentage of Cost Difference for Six-Task Instances
Enumeration	$90,166	$9,406,550	$31,442,800	
CSP	$90,166	$9,406,550	$32,493,900	
Difference	$0	$0	$1,051,100	
Percentage	0.00%	0.00%	3.34%	1.11%
Eight-Task Instances				
Instance	A	B	C	Average Percentage of Cost Difference for Eight-Task Instances
Enumeration	$41,198,700	$10,255,100	$14,897,400	
CSP	$41,584,400	$10,258,700	$14,897,400	
Difference	$385,700	$3,600	$0	
Percentage	0.94%	0.04%	0.00%	0.32%
Ten-Task Instances				
Instance	A	B	C	Average Percentage of Cost Difference for Ten-Task Instances
Enumeration	$36,611,900	$30,321,400	$14,961,700	
CSP	$37,090,900	$31,326,900	$14,963,000	
Difference	$479,000	$1,005,500	$1,300	
Percentage	1.31%	3.32%	0.01%	1.54%
Twelve-Task Instances				
Instance	A	B	C	Average Percentage of Cost Difference for Twelve-Task Instances
Enumeration	$58,682,800	$50,986,300	$55,008,900	
CSP	$59,569,800	$52,053,000	$55,076,100	
Difference	$887,000	$1,066,700	$67,200	
Percentage	1.51%	2.09%	0.12%	1.24%
Average Percentage of Cost Difference for 12 Instances				0.98%

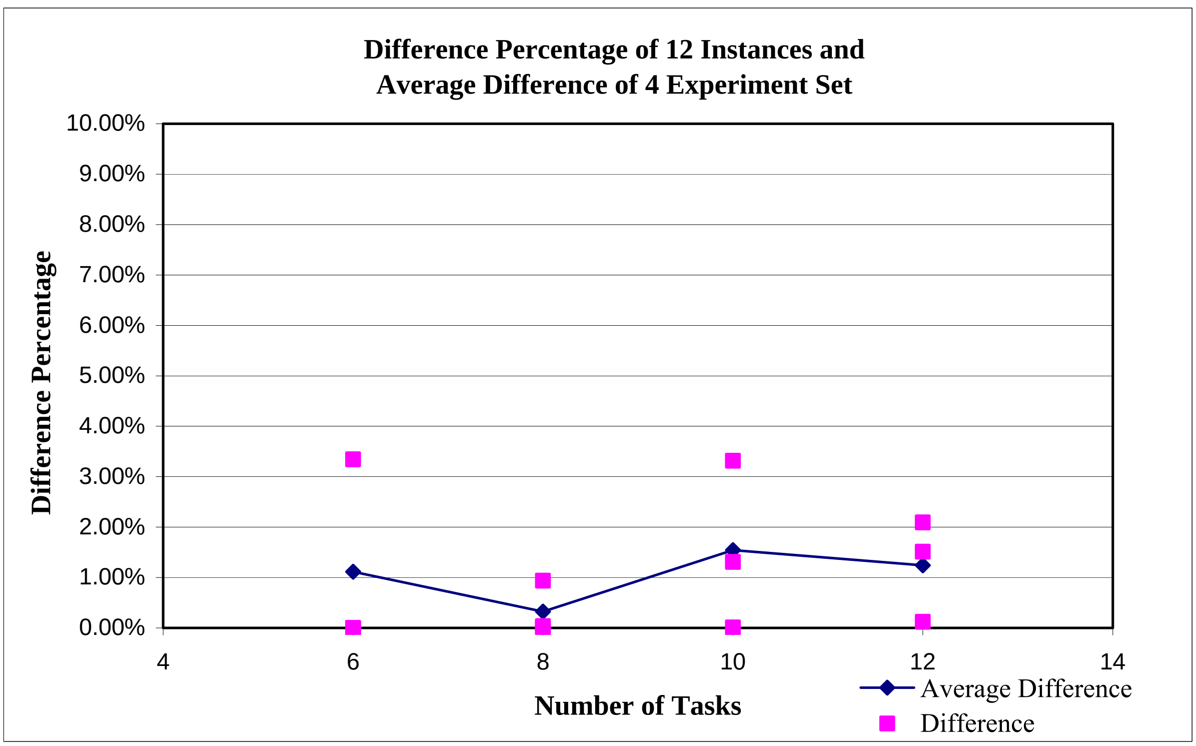

Figure 6-10: Differences and Average Differences of Validation Experiments

6.4 Concluding Remarks

In this chapter, we apply one of the proposed MTS design approaches, the CSP approach, to the MTS design problem of a motor parts manufacturing facility, FORD Saline Plant. We demonstrate the data preparation of the proposed approaches, both for the compact formulation and the CSP approach. The first MTS design for the Saline Plant has 18 task clusters for 27 tasks, for four technology candidates. Three types of technology are selected, unit-load AGV, floor-supported conveyor and overhead trolley conveyor. However, there are some conflicts at the aisle space between unit-load AGV and floor-supported conveyor. By adding flow path crossing constraints and by transforming the conveyor working network, the second MTS design for the Saline Plant has 17 task clusters and two types of technology candidates: unit-load AGV and overhead trolley conveyor. These two MTS designs by the CSP approach show that we only need to sacrifice 0.0015% of total cost to avoid the undesirable flow path crossings.

The MTS designs at the Saline Plant are examples of how the proposed CSP approach can make a contribution in the area of large-scale MTS design problems. The CSP approach is a heuristic approach. Since the existing MTS design of the Saline Plant was not available, we validate the CSP approach by comparing the designs of the CSP approach and those obtained by enumeration on smaller MTS design instances of the Saline Plant. We prepare four sets of experiments with six, eight, ten, and twelve tasks, respectively. Each set of experiment has three instances of MTS design problem whose tasks are selected from the 27 tasks. The results of 12 MTS design instances show that the largest difference by the CSP approach differs from optimality by 3.34%. More importantly, it seems there is no evidence that the difference percentage grows with the increasing of number of tasks.

CHAPTER 7

CONCLUSION

We conclude this dissertation in Section 7.1, summarize the major contributions to research in Section 7.2, and recommend directions for future work in Section 7.3.

7.1 Conclusion

This dissertation focuses on the material transport system design problem (MTSDP), integrating design problems of technology selection and flow network design. This research is motivated by the needs of designing the material transport system in general manufacturing plants. The objective of the MTSDP is to determine the material transport system (MTS) with minimum lifetime costs subject to service requirements, flow network restrictions, and availability of limited resources. In order to further study this problem, we characterize the MTSDP from the perspectives of task requirements, transport technology, and space utilization. A technology classification is proposed so that instances of transport technologies in the same class share the same properties. To facilitate the development of solution approaches of the MTSDP, a decision framework is proposed to emphasize the inter-relationship of three major decisions of the MTSDP: task grouping, flow network design, and task group and technology assignment.

We propose two solution approaches for the MTSDP. The first one is the compact formulation (CF) approach where the three major decisions of the MTSDP are included in a mixed integer non-linear programming (MINLP) formulation. Due to the difficulties of solving large non-linear models, relaxation techniques are applied to linearize the model. The resulting mixed integer linear programming (MILP) formulation can be solved by some powerful commercial solvers e.g., ILOG CPLEX, and its solution value provides a lower bound to the optimal value of the original problem.

Although the compact formulation can be solved by commercial solvers, long solution times might limit its applicability. To reduce solution time, we propose a tightening technique for the MILP. Computational results show that solving an example problem with the tight formulation requires only 26% of the time compared to the original formulation. The memory requirement is also less than 33% compared to the original formulation. The experimental results also show that with the presence of significant control system costs, the designs with multiple-task clusters are more economical than designs restricted to single-task clusters.

The second approach, the clustering/set partition (CSP) approach, decomposes the MTS design process into three phases: task clustering, network connecting, and system selection. For task clustering, we identify the important factors to be used for clustering. We formulate the flow network design problem in a general sense and specify the detailed flow network restrictions for six major transport technology classes. In the last phase, we formulate the system selection problem as a variant of the classical set partition problem to cope with the assignment and resource availability requirements. In general, the clustering/set partition approach is a sequential approach for three intertwined design decisions, with no guarantee of solution optimality.

We perform computational experiments with a small example to compare three approaches: the clustering/set partition approach, a GREEDY approach from the literature, and enumeration. This problem has 9 tasks, 4 technologies, and the largest node size of the working networks is 25. For this example MTS design problem, the proposed clustering/set partition approach finds the optimal solution, while GREEDY yields a solution costing 31.35% more.

Similar comparison with another example is made for the compact formulation and the clustering/set partition approaches. This problem also has 9 tasks, 4 technologies, and the largest node size of the working networks is also 25. The solution value provided by the compact formulation is lower than the optimal value, which was obtained by enumeration. However, the desired empty travel ratios are violated. When the empty travel ratios are enforced in the CF solution, the adjusted solution value is 0.13% higher than the optimal solution.

Finally, we apply the clustering/set partition approach, to a real world application of the MTSDP. The FORD Saline plant is a parts manufacturing facility of one of the largest automotive companies in the world. In this case problem, we show how to compile raw data into appropriate format of the proposed approach, and how to perform network transformation to avoid flow path crossing. We compare the resulting designs with and without flow path crossing constraints. Since the clustering/set partition approach is a heuristic, we perform a set of experiments to verify the solution quality of the approach based on 12 task sets of the Saline plant. The results show that the largest difference from optimality is 3.34%, and the average is 0.98%. More importantly, it seems there is no evidence that the difference percentage grows with an increase in the number of tasks, based on these experiments.

7.2 Research Contributions

Following is a summary of major contributions of this research.

- The Material Transport System Design Problem

To the best of our knowledge, this is the first attempt of studying two isolated problems in the literature, the material transport technology selection problem and the flow network design problem in such an integrated and detailed manner. We consider fixed and variable costs, empty travel, connectivity requirements, arc capacities, directionality, working network, I/O definition, and distance measures in our formulation. From the perspective of technology selection, solving the MTSDP as an integrated problem can make the resulting designs more economical and realistic. From the perspective of flow network design, this research provides solution approaches that allow multiple technologies.

- A Technology Classification and Decision Framework of the MTSDP

To simplify the flow network modeling, we provide a technology classification that categorizes the commonly used transport technologies in manufacturing into six categories. The design decisions involved in the MTSDP are also provided and their relationships are discussed.

- A Compact Formulation for the MTSDP

A compact mixed integer non-linear formulation is proposed for the MTSDP. Some linear approximations techniques are adopted to linearize the model: a set of inequalities provides lower and upper bounds for the empty travel ratio.

- Clustering/Set-Partition Approach for the MTSDP

We also propose a clustering/set partition approach for the MTSDP by synthesizing the methodologies of statistical clustering and optimization into an integrated solution approach. This approach is a heuristic because we only consider a subset of all possible solutions. The solution quality of this approach is validated through a real-world application.

- A Flow Network Design Formulation for Overhead Trolley Conveyors

  Due to the mechanical requirements, overhead trolley conveyor requires a closed trail network structure for its operations. We extend the standard flow network formulation to cover this specialized network structure.

- A Modeling and Network Transformation for Flow Path Crossing Constraints

  To the best of our knowledge, this is the first quantitative method to resolve the flow path crossing conflict. In the literature, previous approaches usually rely on human expertise to avoid flow path crossing.

- A Case Problem based on Real World Data

  Through the literature survey in the domain of material transport system design, we found that there are very few real world applications. In this dissertation, we provide a material transport system design application in the FORD Saline plant, including the data preparation for the proposed approaches.

7.3 Future Research

Following is a summary of some possible research directions based on this research.

- Clustering Criteria and Procedures for Task Clustering

  In this research, we propose three clustering criteria as the distance measures for some hierarchical clustering procedures. These criteria are used for identifying promising task clusters from the perspective of merging, chaining, and balancing flows of tasks. More criteria that concern other aspects of task clustering might benefit the solution qualities of the CSP approach. The incorporation of other clustering procedures, e.g., K-means or other nonhierarchical procedures, may also lead to a more economical MTS design.

- Alternative Solution Algorithms for Flow Network Design Problem of Overhead Trolley Conveyors

  In this research, we solve all flow network design problems by a commercial solver. If such a solver is not available, alternative algorithms are required to provide flow network designs. Fortunately, some previous researches provided such alternatives for some of the flow network design problems, e.g., Balakrishnan (1984) and Bakkalbasi (1990). However, the applicability of these works to the flow network design problem of overhead trolley conveyors requires further investigations.

- Multimode for the Fulfillment of Transportation Requests

  In this research, we do not consider the situations where an individual transportation request can be handled by more than one technology, and thus requires a transfer from one mode to another. In some applications, multimode travel could be a legitimate option. This extension could be made from the proposed approaches by considering possible multimode opportunities for a task and some modeling changes.

- Robust Material Transport System Design

  In this research, we assume that the information of transport requirements, in terms of the quantity and the source/destination of a task, is known with certainty. However, demands change, and this can affect the suitability of an existing MTS design. How to consider demand uncertainty in the design of material transport system is an important research area.

APPENDIX A

COST STRUCTURE

In this section, we provide the cost structure of the technology classes studied in this research. The cost components included are directly related to the procurement and the uses of a technology to perform transportation services. The costs are measured in a pre-specified time period.

Before the detailed discussion of cost structure for each technology class, some general notations are defined here. Let x_{tk} be a binary variable with value 1, if task t is assigned to cluster k; 0, otherwise. Let y_{ij} be a binary variable with value 1, if arc (i, j) is used; 0, otherwise. Let f_{ij}^{t} be a positive continuous variable denote the number of unit flow of task t traversing on arc (i, j).

A.1 Cost Structure of Technology Class E^{VA}

- c_1: Purchase price per unit vehicle

Purchase cost of vehicle = $c_1 \times$ (Number of vehicles)

- c_2: Battery/charger expense per unit vehicle

Power consumption = $c_2 \times$ (Number of vehicles)

- c_3: Maintenance cost per unit vehicle

Maintenance cost (vehicle) = $c_3 \times$ (Number of vehicles)

- c_4: Guide path per unit length

Guide path cost = $c_4 \times$ (length of path segment)

- c_5: Space cost per unit length

Space consumption = $c_5 \times$ (length of path segment)

- c_6: Maintenance cost per unit length

Maintenance cost (Guide path) = $c_6 \times$ (length of path segment)

- c_7: Merges/diverges/connections cost per unit length

Connection cost = $c_7 \times$ (length of path segment)

Consider a material transport (sub) system, task-resource combination k, whose transport technology belongs to technology class E^{VA}. Denote d_{ij} to be the distance of arc (i, j), μ to be the operating speed of the technology, and t_a to be the time available of a technology for operation in a time period. The number of vehicles required for arc (i, j) per time period, $\Phi(i, j)$, can be approximated as follows.

$$\Phi(i, j) = \frac{d_{ij}}{t_a \mu} \sum \left(f_{ij}^t : t \in T(k) \right) \qquad \text{(A.1)}$$

Let $vc_{ij}(VA)$ denotes the cost of unit flow traverse on arc (i, j). $vc_{ij}(VA)$ and the network operating cost of a E^{VA} system, $C^v(E^{VA})$, can be modeled as follows..

$$vc_{ij}(VA) = (c_1 + c_2 + c_3)\frac{d_{ij}}{t_a s}$$

$$C^v(E^{VA}) = \sum \ \sum (vc_{ij}(VA) f_{ij}^t : t \in T_k, (i, j) \in A_k) \qquad \text{(A.2)}$$

Let $fc_{ij}(VA)$ denotes the cost of including arc (i, j). $fc_{ij}(VA)$ and the network construction cost of an E^{VA} system, $C^f(E^{VA})$, can be modeled as follows.

$$fc_{ij}(VA) = (c_4 + c_5 + c_6 + c_7) d_{ij}$$

$$C^f(E^{VA}) = \sum \left(fc_{ij}(VA) y_{ij} : (i, j) \in A_k \right) \qquad \text{(A.3)}$$

The cost of control system of an E^{VA} system, $C^C(E^{VA})$, is modeled as the sum of a fixed cost C^{C1}, incurred when the control device is purchased, and a incremental cost, C^{C2}, increased proportionally with the number of tasks serviced.

$$C^C(E^{VA}) = \sum_{t\in T_k}\left(C^{C1}x_{kk} + C^{C2}\sum_{t\in T_k}x_{tk}\right) \tag{A.4}$$

Let $CC(E^{VA})$ denote the capital investment of a task-resources combination k and $CC(E^{VA})$ can be modeled as follows:

$$CC(E^{VA}) = c_1\sum\left(\Phi(i, j) : (i, j) \in A_k\right) + \sum(c_4 + c_5 + c_7)d_{ij}y_{ij} : (i, j) \in A_k + C^C\left(E^{VA}\right) \tag{A.5}$$

Let $TC(E^{VA})$ denote the total cost of a task-resources combination k and $TC(E^{VA})$ can be modeled as follows:

$$TC(E^{VA}) = C^v(E^{VA}) + C^f(E^{VA}) + C^C(E^{VA}) \tag{A.6}$$

A.2 Cost Structure of Technology Class E^{VM}

- c_1: Purchase price per unit vehicle

Purchase cost of vehicle = $c_1 \times$ (Number of vehicles)

- c_2: Operating personnel

Labor cost = $c_2 \times$ (Number of vehicles)

- c_3: Power and/or fuel consumption per unit vehicle

Power consumption = $c_3 \times$ (Number of vehicles)

- c_4: Maintenance cost per unit vehicle

Maintenance cost = $c_4 \times$ (length of path segment)

- c_5: Space cost per unit length

Space consumption = $c_5 \times$ (length of path segment)

- c_6: Maintenance cost per unit length

Maintenance cost (flow path) = $c_6 \times$ (length of path segment)

Consider a material transport (sub) system, task-resource combination *k*, whose transport technology belongs to technology class E^{VM}. The number of vehicles required can be obtained by formula (A.1).

Let $vc_{ij}(VM)$ denotes the cost of unit flow traverse on arc (i, j). $vc_{ij}(VM)$ and the network operating cost of a E^{VM} system, $C^{v}(E^{VM})$, can be modeled as follows.

$$vc_{ij}(VM) = (c_1 + c_2 + c_3 + c_4)\frac{d_{ij}}{t_a \mu}$$

$$C^{v}(E^{VM}) = \sum \sum (vc_{ij}(VM) f_{ij}^{t} : t \in T(k), (i, j) \in A_k) \quad \text{(A.7)}$$

Let $fc_{ij}(VM)$ denotes the cost of including arc (i, j). $fc_{ij}(VM)$ and the network construction cost of an E^{VM} system, $C^{f}(E^{VM})$, can be modeled as follows.

$$fc_{ij}(VM) = (c_5 + c_6) d_{ij}$$

$$C^{f}(E^{VM}) = \sum \left(fc_{ij}(VM) y_{ij} : (i, j) \in A_k \right) \quad \text{(A.8)}$$

The cost of control system of an E^{VM} system, $C^{C}(E^{VM})$, is modeled as the sum of a fixed cost C^{C1}, incurred when the control device is purchased, and a incremental cost, C^{C2}, increased proportionally with the number of tasks serviced.

$$C^{C}(E^{VM}) = \sum_{t \in T_k} \left(C^{C1} x_{kk} + C^{C2} \sum_{t \in T_k} x_{tk} \right) \quad \text{(A.9)}$$

Let $CC(E^{VM})$ denote the capital investment of a task-resources combination *k* and $CC(E^{VM})$ can be modeled as follows:

$$CC(E^{VM}) = c_1 \sum \left(\Phi(i, j) : (i, j) \in A_k \right) + \sum c_5 d_{ij} y_{ij} : (i, j) \in A_k + C^{C}\left(E^{VM}\right) \quad \text{(A.10)}$$

Let $TC(E^{VM})$ denote the total cost of a task-resources combination *k* and $TC(E^{VM})$ can be modeled as follows:

$$TC(E^{VM}) = C^v(E^{VM}) + C^f(E^{VM}) + C^C(E^{VM}) \quad \text{(A.11)}$$

A.3 Cost Structure of Technology Class E^C

- c_1: Purchase price per unit length

Purchase cost of conveyor = $c_1 \times$ (Number of unit length)

- c_2: Power consumption of loaded travel per unit length

Power consumption (loaded) = $c_2 \times$ (Utilization)

- c_3: Power consumption of empty travel per unit length

Power consumption = $c_3 \times$ (1 - Utilization)

- c_4: Maintenance cost per unit length

Maintenance cost = $c_4 \times$ (length of path segment)

- c_5: Space cost per unit length

Space consumption = $c_5 \times$ (length of path segment)

- c_6: Merges/diverges/connections cost per segment

Connection cost = $c_6 \times$ (length of path segment)

Denote l to be the unit length of conveyor e. The number of unit length required for arc (i, j) can be approximated by $\frac{1}{l} d_{ij}$. The utilization of conveyor e on arc (i, j), $U(i, j)$, can be approximated as follows:

$$U(i, j) = \frac{d_{ij}}{t_a \mu} \sum \left(f_{ij}^t : t \in T(k) \right) \quad \text{(A.12)}$$

Let $vc_{ij}(C)$ denotes the cost of unit flow traverse on arc (i, j). $vc_{ij}(C)$ and the network operating cost of a E^C system, $C^v(E^C)$, can be modeled as follows:

$$vc_{ij}(C) = c_2 \frac{d_{ij}}{t_a \mu} + c_3 \left(1 - \frac{d_{ij}}{t_a \mu} \right) = c_3 + (c_2 - c_3) \frac{d_{ij}}{t_a \mu}$$

$$C^{v}(E^{C}) = \sum \ \sum (vc_{ij}(C) f_{ij}^{t} : t \in T(k), (i,j) \in A_k) \tag{A.13}$$

Let $fc_{ij}(C)$ denotes the cost of including arc (i, j). $fc_{ij}(C)$ and the network construction cost of an E^C system, $C^f(E^C)$, can be modeled as follows.

$$fc_{ij}(C) = \left(\frac{1}{l} c_1 + c_4 + c_5 + c_6 \right) d_{ij}$$

$$C^{f}(E^{C}) = \sum \left(fc_{ij}(C) y_{ij} : (i,j) \in A_k \right) \tag{A.14}$$

The cost of control system of an E^C system, $C^C(E^C)$, is modeled as the sum of a fixed cost C^{C1}, incurred when the control device is purchased, and a incremental cost, C^{C2}, increased proportionally with the number of tasks serviced.

$$C^{C}(E^{C}) = \sum_{t \in T_k} \left(C^{C1} x_{kk} + C^{C2} \sum_{t \in T_k} x_{tk} \right) \tag{A.15}$$

Let $CC(E^C)$ denote the capital investment of a task-resources combination k and $CC(E^C)$ can be modeled as follows:

$$CC(E^{C}) = c_1 \frac{d_{ij}}{l} + \sum \left((c_5 d_{ij} + c_6) y_{ij} : (i,j) \in A_k \right) + C^{C}\left(E^{C}\right) \tag{A.16}$$

Let $TC(E^C)$ denote the total cost of a task-resources combination k and $TC(E^C)$ can be modeled as follows:

$$TC(E^{C}) = C^{v}(E^{C}) + C^{f}(E^{C}) + C^{C}(E^{C}) \tag{A.17}$$

A.4 Cost Structure of Technology Class E^{OP} and E^{OT}

- c_1: Purchase price per unit carrier

Purchase cost of carrier = $c_1 \times$ (Number of carriers)

- c_2: Power consumption per unit carrier

Power consumption = $c_2 \times$ (Number of carriers)

- c_3: Maintenance cost per unit vehicle

Maintenance cost (carrier) = $c_3 \times$ (Number of carriers)

- c_4: Hardware support (track) per unit length

Guide path cost = $c_4 \times$ (length of path segment)

- c_5: Maintenance cost per unit length

Maintenance cost (guide path) = $c_5 \times$ (length of path segment)

- c_6: Merges/diverges/connections cost per unit length

Connection cost (Guide path) = $c_6 \times$ (length of path segment)

The cost structure of technology class E^{OP} and E^{OT} are the same. For ease of illustration, technology class E^{O} is used as representative class. The number of carriers required on arc (i, j) can be obtained by the formula (A.1).

Let $vc_{ij}(O)$ denotes the cost of unit flow traverse on arc $(i, j), vc_{ij}(O)$ and The network operating cost of a E^{O} system, $C^{v}(E^{O})$, can be modeled as follows.

$$vc_{ij}(O) = (c_1 + c_2 + c_3)\frac{d_{ij}}{t_a \mu}$$

$$C^{v}(E^{O}) = \sum \ \sum (vc_{ij}(O) f_{ij}^{t} : t \in T(k), (i, j) \in A_k) \qquad \text{(A.18)}$$

Let $fc_{ij}(O)$ denotes the cost of including arc (i, j). $fc_{ij}(O)$ and the network construction cost of an E^{O} system, $C^{f}(E^{O})$, can be modeled as follows:

$$fc_{ij}(O) = (c_4 + c_5 + c_6) d_{ij}$$

$$C^{f}(E^{O}) = \sum \left(fc_{ij}(O) y_{ij} : (i, j) \in A_k \right) \qquad \text{(A.19)}$$

The cost of control system of an E^{O} system, $C^{C}(E^{O})$, is modeled as the sum of a fixed cost C^{C1}, incurred when the control device is purchased, and a incremental cost, C^{C2}, increased proportionally with the number of tasks serviced.

$$C^{C}(E^{O}) = \sum_{t \in T_k} \left(C^{C1} x_{kk} + C^{C2} \sum_{t \in T_k} x_{tk} \right) \quad \text{(A.20)}$$

Let $CC(E^{O})$ denote the capital investment of a task-resources combination *k* and $CC(E^{O})$ can be modeled as follows:

$$CC(E^{O}) = c_1 \sum (\Phi(i, j) : (i, j) \in A_k) + \sum ((c_4 d_{ij} + c_6) y_{ij} : (i, j) \in A_k) + C^{C}(E^{O}) \quad \text{(A.21)}$$

Let $TC(E^{O})$ denote the total cost of a task-resources combination *k* and $TC(E^{O})$ can be modeled as follows:

$$TC(E^{O}) = C^{v}(E^{O}) + C^{f}(E^{O}) + C^{C}(E^{O}) \quad \text{(A.22)}$$

A.5 Cost Structure of Technology Class E^B

- c_1: Power consumption per unit distance

Power consumption = $c_1 \times$ (travel distance per time period)

- c_2: Maintenance cost
- c_3: Purchase cost of hoist
- c_4: Hardware support (track) per unit length

Guide path cost = $c_4 \times$ (length of rectangle)

- c_5: Maintenance cost per unit length

Maintenance cost (guide path) = $c_5 \times$ (length of rectangle)

Let $vc_{ij}(B)$ denotes the cost of unit flow traverse on from node *i* to node *j* and $L_{\infty}(i, j)$ denotes to be the Chybechev distance between node *i* and *j*. $vc_{ij}(B)$ and the network operating cost of a E^B system, $C^{v}(E^{B})$, can be modeled as follows.

$$vc_{ij}(B) = c_1 L_{\infty}(i, j)$$

$$C^{v}(E^{B}) = \sum \sum (vc_{ij}(B) f_{ij}^{t} : t \in T_k, i \in o(t), j \in d(t)) \quad \text{(A.23)}$$

Let $fc_{ij}(B)$ denotes the unit fixed cost of an E^B system, cost of rectangle with length d_{ij}. $fc_{ij}(B)$ and the network construction cost of an E^B system, $C^f(E^B)$, can be modeled as follows.

$$fc_{ij}(B) = c_4 + c_5$$

$$C^f(E^B) = fc_{ij}(B)d_{ij} + c_2 + c_3 \tag{A.24}$$

The cost of control system of an E^B system, $C^C(E^B)$, is modeled as the sum of a fixed cost C^{C1}, incurred when the control device is purchased, and a incremental cost, C^{C2}, increased proportionally with the number of tasks serviced.

$$C^C(E^B) = \sum_{t \in T_k}\left(C^{C1} x_{kk} + C^{C2} \sum_{t \in T_k} x_{tk} \right) \tag{A.25}$$

Let $CC(E^B)$ denote the capital investment of a task-resources combination k and $CC(E^B)$ can be modeled as follows:

$$CC(E^B) = c_2 + c_3 + c_4 d_{ij} + C^C\left(E^B\right) \tag{A.26}$$

Let $TC(E^B)$ denote the total cost of a task-resources combination k and $TC(E^B)$ can be modeled as follows:

$$TC(E^B) = C^v(E^B) + C^f(E^B) + C^C(E^B) \tag{A.27}$$

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