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Integration of operation allocation and material handling in the design of flexible manufacturing systems.

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Integration of Operation Allocation and Material Handling in the Design of Flexible Manufacturing Systems

By

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Abstract

Operation Allocation and Material Handling Systems Selection are important functions of a manufacturing system and as such must be considered within an integrated approach to manufacturing systems design. This work, an extension to the work done by Paulo (1999) proposes to integrate two important functions of manufacturing, i.e. operation allocation and material handling systems selection, and solve them iteratively. The objective of the operation allocation model is to select a group of machines where the operations of the part types will be performed and then to assign those operations to the selected machines. The material handling equipment is allocated by the material handling system selection model to transport a part type from one machine to the other for the next operation. The operation allocation model obtains one of its inputs from the material handling system selection model in the form of material handling equipment to be used for transporting a part type from one machine to another machine. The operation allocation model interfaces with the material handling system selection model by providing input data in the form of the manufacturing operations to be performed at each machining center. The material handling system is selected on the basis of the parts visiting a machining center to perform a manufacturing operation and the abilities of the handling devices to perform the required material handling functions of those part types. The material handling system selection model provides the feedback to the first model to complete the iteration. A program was developed to solve the two models iteratively so as to obtain an optimal solution.

Dedication

I dedicate this work to my family Amarjit Singh, Inderjit Kaur and Navpreet Boparai and my friends, who through consistent support and sacrifices helped me complete my master's thesis. Their support and help in every aspect will be remembered for all times to come

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model

d_i = demand for part type i

$\alpha_{h\hat{h}sijp}$ = requirements matrix for $(h\hat{h})$ combinations

$t_{h\hat{h}e}$ = time for equipment e to perform the $(h\hat{h})$ combinations

$\hat{W}_{it}$ = relative weight of the product variable t on part type i

W_{et} = relative weight of the product variable t on material handling equipment e

$W_{h\hat{h}e}$ = relative degree of capability of material handling equipment e to perform the operation/sub-operation combination $h\hat{h}$

C_{ei} = compatibility factor between a piece of material handling equipment e and part type i

CHAPTER 1. INTRODUCTION

Today's market is determined by consumers. For producers to exist, they must seek and produce what potential consumers require. This statement could have been a laughing matter if it was stated at the turn of the 20th century when Henry Ford stated, "People can order any color as long as it is black". At that time, markets were national and foreign competition was not a problem.

1.1. Background

The Second World War brought a new era to manufacturing and international trade, which started expanding at an enormous rate after the war ended. Industrialized countries found that they could improve their economy only by discovery of new materials and production techniques to increase their productivity, which could result in lower prices of their products. Therefore, efficiency became symbolic and the most important factor in the design and operations of systems. Two decades later, the competition widened to a global realm and consumers' purchasing power increased. Apart from quality, meeting the dynamic changes in customer's demands became the major deciding factor of a company's success. The researchers began to shift focus towards flexible manufacturing systems, which would not only enhance flexibility but also the overall productivity of manufacturing systems. Fierce worldwide competition forced the industrial organizations to apply more and more computer technology in manufacturing. Still CAD/CAM/CIM could not increase the performance of the systems and the focus shifted to total integration of the various functions of manufacturing.

Manufacturing is a set of functions, which coordinate to manufacture a product with increased productivity. Each function contributes value to the product and comes with a cost. Hence, the cost of production becomes an important criterion for the success of a manufacturing organization. Lately, the material handling function started gathering a lot of attention from researchers. It contributes a substantial share in total manufacturing cost of the product. Tompkins and White (1996) stated that material handling accounts for 25% of all employees, 55% of all factory space, and 87% of production time. Material handling costs are estimated to represent between 15 and 70% of the total cost of manufacturing a product. Certainly, material handling is one of the first places to look for cost reduction.

Since all the functions of manufacturing are interdependent, it is necessary to view the manufacturing operations as an integrated system of various subsystems. For successful integration, the information flow amongst subsystems becomes a very crucial factor.

1.2. Motivation of the Research Work

Increase in demand for flexibility in the manufacturing systems has been the motivating factor behind the large volume of research in the area of flexible manufacturing systems (FMS). Though FMS provide flexibility to manufacturing systems, until total integration is achieved, the overall increase in productivity would be minimal, a subject that has drawn a great deal of attention from the research community. The material handling design problem, one of the key components in an integrated manufacturing system, predominantly interacts with the facility layout and system control/scheduling problems. The MHS design problem as a whole requires that the logical and physical aspects of material flow be combined by means of material handling equipment and that the design be justified from both a performance and an economic perspective. The economic justification of technology in integrated systems is a major concern in MHS design. Manufacturing systems are highly complex by nature. Since MHSs are an integrating component of a manufacturing system, all complexity that is inherent in the manufacturing problem is translated to the material-handling system. Associated with the MHS design problem is the complexity of the economic justification process. All design is of no value if the resulting design is economically infeasible. Therefore, the breadth of the MHS design problem must include the economic justification. However much of the recent research relegates the economics of the design to a secondary issue that is evaluative in nature.

One of the principal tasks of flexible manufacturing systems is to make the optimal selection of machines and the allocation of part operations to the selected machines. The objective of the task is to minimize the cost of operation, machine set-up and material handling costs, minimization of the number of machines allocated to each cell minimization of total processing times, maximization of machine utilization, etc. Among the material handling operations, the transportation operation is a major one, which contributes substantially to the total material handling cost.

Paulo, et al. (1999) and Paulo (2000) made a first attempt at integrating the operation allocation problem (OA) and the material handling (MH) system selection problem.

However, they proposed a sequential solution approach. For the reasons explained above, it is proposed to extend the above work by integrating the two problems, and by developing an iterative solution procedure, which is based on feed forward and feedback loops between the two models, in order to obtain an overall optimal solution to the models.

1.3. Outline of the Thesis Work

The thesis is divided into six chapters. Chapter 1 is an introduction where some background on the current problems and the motivation for this work are explained. Chapter 2 presents a literature review of previous research work on the operation allocation and material handling system selection problems. The research objectives of this work are further defined at the end of that chapter. The operation allocation and material handling system selection models are then developed and presented in chapter 3. The next chapter presents an illustrative example that is solved and a discussion of its solution. Chapter 5 describes the OA and MH Solver program developed using Visual Basic 6.0. Analysis and discussion of the implementation of the model, some concluding remarks about the current work and scope of future work to be undertaken are presented in chapter 6.

CHAPTER 2. LITERATURE REVIEW

2.1. Review of the Related Literature

2.1.1. Review of Operation Allocation Literature

The operation allocation problem in a flexible manufacturing system has been of continuing interest to researchers. Although several approaches have been proposed to solve the problem, for the purpose of this work, emphasis has been given to mathematical programming approaches. The emphasis is placed on those models that were developed primarily for flexible manufacturing systems.

Lashkari, et al. (1987) proposed the integration of the operation allocation problem with the planning aspects of refixturing and limited tool availability. The problem was formulated as a non-linear 0-1 integer programming formulation with double objective functions. The objective functions consist of minimization of transport load and minimization of refixturing activities.

Wilson (1989) presented an alternative 0-1 integer programming formulation to the one proposed by Lashkari, et al. (1987). In addition to the planning aspects of refixturing and limited tool availability, the alternative formulation avoided the non-linearities of the previous approach in a new integer programming formulation. The problem of minimization of transport load is formulated.

Damodaran, et al. (1992) proposed a mixed integer programming model for operation allocation problem. The model is suitable for multi-machine and multiple cell environments. The objective function minimizes the refixturing costs, material handling and processing costs. The allocation of operations is effected by the trade-off between refixturing and material handling.

Taboun and Ulger (1992) presented a 0-1 integer programming formulation for operation allocation in flexible manufacturing systems. The multi-objective model considers different objectives such as the minimization of processing, handling, tool set-up, fixturing/refixturing and penalty costs of under-utilization and over-loading of machining centers.

Atmani, et al. (1995) proposed a 0-1 integer programming model that jointly considers operation allocation and cell formation in cellular manufacturing. The objective function minimizes the operation costs, refixturing costs and transportation costs.

Mohamed (1998) proposed that operations planning and scheduling problems in advanced manufacturing systems, such as flexible manufacturing systems, are composed of a set of interrelated problems, such as part-type batching, machine grouping, tool loading, routing part input sequencing and on-line scheduling. He developed a detailed simulation model, which integrated loading, part inputting, routing and dispatching issues.

Guerrero, et al. (1999) presented a new approach to the loading problem in flexible manufacturing systems. It focuses on the existence of alternative routes for each part type. Also, the optimal number of copies of each tool type to be loaded into each tool magazine was directly determined. The loading objective was to balance the machine workloads. The problem was modeled as a mixed-integer linear program.

Joines, et al. (1996) proposed an integer program that is solved using a genetic algorithm to assist in the design of cellular manufacturing systems. It assumes that the design of a cellular manufacturing system require that part population should be divided in part families and the associated plant equipment be partitioned into machine cells. The formulation was a unique representation scheme for individuals (part/machines partitions) that reduces the size of the cell formation problem and increases the scale of problem that can be solved. This approach offers improved design flexibility by allowing a variety of evaluations of functions to be employed and by incorporating design constraints during formation.

Vidyarthi and Tiwari (2000) developed a genetic algorithm based heuristic to solve the machine-loading problem of a random type FMS. The objective of the loading problem was to minimize the system unbalance and maximize the throughput, satisfying the technological constraints such as availability of machine time etc.

2.1.2. Review of Material Handling System Selection Literature

The importance of material handling system and facility design has been confirmed many times over the years with respect to its production support role and cost impact. Thus they have been attracting considerable attention from researchers. Many different approaches have been proposed in the past and recent literature to solve the problem of making a choice of an appropriate material handling equipment for a part type.

Since the scope of the problem is quite large and the problem in itself becomes too complex, not many mathematical programming models have been proposed for this problem. Attempts have been made to optimize the material flow system design but not the overall manufacturing system. If the material flow design can't be integrated into the overall manufacturing system, it may have a negative impact on the overall system performance. Rembold and Tanchoco (1994) have illustrated this aspect of material flow systems in manufacturing.

Hassan, et al. (1985) developed an algorithm that selects a material handling equipment and assigns it to an interdepartmental move i.e. transportation. The problem is formulated as an integer program with the objective of minimizing the total operating and investment costs of the selected equipment. The problem only considers one type of departmental move, i.e. transportation, and other moves are not taken into the scope of the problem.

Other integrated approaches have been proposed. Noble, et al. (1998) developed a model that integrates material handling equipment selection and specification (material handling interface equipment included) and path/load dependent unit load size. The formulation attempts to minimize the operating and capital cost of material handling and the necessary interface equipment. Although the material handling operations are not defined, the model appears to only consider transportation between workplaces.

Gupta and Dutta (1994) proposed a methodology so that material handling could be considered within the manufacturing systems design through concurrent engineering. The emphasis was placed on the material handling systems, rather than individual material handling equipment. The approach adopts five key product variables and different operations and sub-operations for material handling equipment, developed by Ayres

(1988). The appropriate material handling system is then selected through a weighted rating method.

Atmani and Dutta (1996) proposed a mathematical model to select material handling system, based on the methodology developed by Gupta and Dutta (1994). For a 0-1 integer-programming model, an adaptability factor was maximized. Gupta and Dutta (1994) defined it as "the ratio of basic motions/movements that are required by a new product to those available in the current manufacturing logistics systems".

Noble and Chittratanawat (1999) also presented an integrated model for solving the facility layout, pickup/drop-off locations and material handling equipment selection problems. The problem of facility design was formulated as a nonlinear mixed integer program. The model simultaneously determines the facility locations, pickup/drop-off points and material handling equipment. The approach not only integrates many of the significant factors in the facilities design, it also minimizes the overall facility design costs.

In recent years, there has been a tendency to consider the material handling system as a whole and not the individual piece of equipment. Moreover, there has been an interest on the part of researchers in integrating the operation allocation and material handling system selection problems. But due to the complexity of the problem, few works have been reported in this area.

Paulo (2000) and Paulo, et al. (1999) did pioneering work in an attempt to integrate the two functions. They presented a 0-1 integer-programming formulation consisting of two models, i.e., the operation allocation and the material handling system selection that were solved sequentially. The objective function of operation allocation model consisted of minimizing the cost of operation, machine set up cost and transportation cost. The objective of the model was to select a group of machines where the operations of the part types could be performed and then assigning these operations to the selected machines. The problem of material handling system selection is to maximize the compatibility of a piece of equipment and a part type. It assumed that a part type can be divided into a number of key product variables that define the choices of manufacturing technology (complexity, precision, diversity, batch size and mass or linear dimension). The compatibility of a part type and equipment is defined by these variables. The model assumes that each material handling operation can be divided into five major categories: loading/unloading at the workplace, transportation, handling/rehandling away from the workplace, inspection module and storage/retrieval. Each of these operations is associated with a number of sub-operations such as orientation change, position change, quantity change, sequence change and timing change. The attributes of the product/process combination, i.e. choice of technology, are related to the material handling system requirements through a five point rating scale. The appropriate material handling system is then selected through a weighted rating method. This formulation attempts to maximize the measure of compatibility of a part type and a piece of material handling equipment for a given operation to be performed on a machine. The model seeks input from the output of the operation allocation problem solution. Thus, this approach made a successful attempt towards integration of the operation allocation and material handling problems in FMS.

2.1.3. Comments and Analysis

As mentioned above, Paulo (2000) solved the operation allocation and material handling systems selection problems in a sequential manner. The solution to the operation allocation problem provided the necessary input to the material handling system selection problem. However, there was no feedback from the material handling system selection problem to the operation allocation problem. In as much as operation allocation and material handling are two interdependent functions in a manufacturing system, it is necessary to also to have a feedback loop from the material handling system selection model to the operation allocation model. The proposed research work in this thesis is to develop the feedback loop and to complete the integration process.

CHAPTER 3. THE MATHEMATICAL MODELS

The mathematical models presented in this chapter are based on the work reported in Paulo, et al. (1999) and Paulo (2000). These models were suitably modified and extended for the scope of the current proposal, which seeks to develop an iterative solution procedure for the two models. The operation allocation and material handling systems are subsets of an integrated manufacturing system and are interrelated. Thus it becomes necessary to solve the two models iteratively to arrive at an optimal solution. To facilitate the integration, the operation allocation model was changed substantially, and some changes were introduced to the material handling system selection model to enable the flow of information between the two models.

3.1. Sub-Model 1. Operation Allocation

The operation allocation model in FMS as proposed by Paulo, et al. (1999) was modified appropriately to account for material handling costs in the objective function. An index *e* for MH equipment was added to the decision variable to track the choice of material handling equipment (transportation cost) to transport a part type from one machine to the next. A constraint was added to make sure that only one MH equipment was chosen for each (part type, process plan, operation, machine) combination. The results from the operation allocation model are summarized in a new matrix $A_{sj}(ip)$, which carries the index *p* for reasons to be explained later in this section.

3.1.1. Mathematical Formulation

We assume a set of n part types labeled with the indices $i = 1, ..., n$, where part type i has the known and uniform demand d_i over the planning period. A part type i can be processed under different process plans $p = 1, \ldots, P(i)$. A part type-process plan combination is designated as (ip). For an (ip) combination, the manufacturing operations are represented by the indices $s = 1, ..., S(ip)$. There is a set of m machines labeled with the indices $j = 1, ..., m$. A number of material handling devices are available for transportation. These are labeled as $e = 1, ..., E$.

The operation allocation model involves the assignment of operations of each part type to appropriate machines to minimize the total costs of manufacturing operations, machine setups and material handling. The 0-1 decision variables are denoted by $X_{sje}(ip)$, where $X_{sje}(ip) = 1$ if operation s of (ip) is performed on machine j, and MH equipment e is used for transportation to the next machine, and zero otherwise. The operation cost is given by $E_1(X_{sje}(ip))$:

$$E_1(X_{sje}(ip)) = \sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{j \in J_{ips}} \sum_{e \in E_{ips}} OC_{sj}(ip) X_{sje}(ip) \qquad (1)$$

where, $OC_{sj}(ip)$ is the given cost of operation s of a unit of (ip) on machine j. This includes both the manufacturing cost and the refixturing cost. The set of machines that can perform manufacturing operation s of (ip) is given by J_{ips}. E_{ips} represents the set of equipment that is available to transport (ip) after operation s is completed at a machine

The machine setup cost is given by $E_2(M_j)$:

$$E_2(M_j)=\sum_{j=1}^{m} SC_j M_j \tag{2}$$

where SC_j is the known setup cost for machine j and the auxiliary variable M_j takes the value of one if machine j is selected and zero otherwise.

The material handling cost is given by $\dot{E}_3(X_{sje}(ip))$:

$$\dot{E}_3(X_{sje}(ip)) = \sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{j\in J_{ips}} \sum_{\acute{j}\in J_{ip(s+1)}} \sum_{e\in E_{ips}} \sum_{\acute{e}\in E_{ip(s+1)}} T_{iej\acute{j}} X_{sje}(ip) X_{(s+1)\acute{j}\acute{e}}(ip) \tag{3}$$

where $T_{iej\acute{j}}$ is the cost of moving a unit of part type i from machine j to machine $\acute{j}$ for the next operation using MH equipment e for transportation. Since $\dot{E}_3(X_{sje}(ip))$ is a nonlinear function, the linearization technique given in Taha (1987) is applied. This prescribes replacing $\dot{E}_3(X_{sje}(ip))$ with

$$E_3(L_{sj\acute{j}e\acute{e}}(ip)) = \sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{j\in J_{ips}} \sum_{\acute{j}\in J_{ip(s+1)}} \sum_{e\in E_{ips}} \sum_{\acute{e}\in E_{ip(s+1)}} T_{iej\acute{j}} L_{sj\acute{j}e\acute{e}}(ip) \tag{4}$$

where $L_{sj\acute{j}e\acute{e}}(ip)$ is a new 0-1 integer variable satisfying the following two sets of constraints:

$$X_{sje}(ip) + X_{(s+1)\hat{j}\hat{e}}(ip) - 2L_{sj\hat{j}e\hat{e}}(ip) \geq 0 \qquad \forall i, p, s \in \{1,2,\dots,S(ip)-1\}, \quad (5)$$

$$e \in E_{ips}, \hat{e} \in E_{ip(s+1)}, j \in J_{ips}, \hat{j} \in J_{ip(s+1)}$$

$$X_{sje}(ip) + X_{(s+1)\hat{j}\hat{e}}(ip) - L_{sj\hat{j}e\hat{e}}(ip) \leq 1 \qquad \forall i, p, s \in \{1,2,\dots,S(ip)-1, \quad (6)$$

$$e \in E_{ips}, \hat{e} \in E_{ip(s+1)}, j \in J_{ips}, \hat{j} \in J_{ip(s+1)}$$

The set of constraints given above ensures that $L_{sj\hat{j}e\hat{e}}(ip)$ takes the value one if and only if (*ip*) moves from machine *j* using MH equipment *e*, after performing operation *s* to machine $\hat{j}$ to perform operation (*s+1*).

The objective of the model is therefore to determine the values of $X_{sje}(ip)$ and $L_{sj\hat{j}e\hat{e}}(ip)$ that will minimize the total operating, machine set-up and material handling costs; it is mathematically expressed as:

$$\text{Min} \qquad E_1(X_{sje}(ip)) + E_2(M_j) + E_3(L_{sj\hat{j}e\hat{e}}(ip)) \qquad (7)$$

Next, the constraints are developed for the model. The first constraint set ensures that each part type is processed under a single process plan, and it is represented by:

$$\sum_{p=1}^{P(i)} Z(ip) = 1 \qquad \forall i \qquad (8)$$

where Z(*ip*) = 1 if part type *i* is processed under process plan *p* and zero otherwise.

The following constraints set ensures that once a process plan is selected for a part type, each operation in that plan uses only one of the available MH equipment for a given operation. It is represented by:

$$\sum_{e \in E_{ips}} Y_{se}(ip) = Z(ip) \qquad \forall i, p, s \qquad (9)$$

The following constraints set ensures that once a MH equipment is chosen for an (*ip*) combination, each corresponding operation is processed on only one of the available machines. It is represented by:

$$\sum_{j \in J_{ips}} X_{sje}(ip) = Y_{se}(ip) \qquad \forall i, e, p, s \qquad (10)$$

The following constraints set ensures that if machine *j* is selected then at least one operation must be assigned to it. It is represented by:

$$\sum_{i=1}^{n} \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{e \in E_{ips}} X_{sje}(ip) \geq M_j \qquad \forall j \qquad (11)$$

The following constraints set ensures that the total time required by the operations allocated to a machine *j*, once it is selected, does not exceed the machine's known capacity. It is represented by:

$$\sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{e \in E_{ips}} t_{sj}(ip) X_{sje}(ip) \le b_j M_j \qquad \forall j \tag{12}$$

where $t_{sj}(ip)$ is the time to perform operation s of (ip) combinations on machine j. The two sets of constraints, (11) and (12), ensure consistency between the allocation of operations of the part types to machines and the selection of machines.

Assembling the above objective function and constraints, we get the following complete statement of our 0-1 mathematical programming model of the operation allocation model, designated as P (OA).

P (OA): Minimize

$$\sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{j \in J_{ips}} \sum_{e \in E_{ips}} OC_{sj}(ip) X_{sje}(ip) + \sum_{j=1}^{m} SC_j M_j$$
$$+ \sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{j \in J_{ips}} \sum_{\hat{j} \in J_{ip(s+1)}} \sum_{e \in E_{ips}} \sum_{\hat{e} \in E_{ip(s+1)}} T_{ie\hat{j}} L_{sj\hat{j}e\hat{e}}(ip) \tag{13}$$

Subject to

$$\sum_{p=1}^{P(i)} Z(ip) = 1 \qquad \forall i \tag{14}$$

$$\sum_{e \in E_{ips}} Y_{se}(ip) = Z(ip) \qquad \forall i, p, s \tag{15}$$

$$\sum_{j \in J_{ips}} X_{sje}(ip) = Y_{se}(ip) \qquad \forall i, e, p, s \tag{16}$$

$$\sum_{i=1}^{n} \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{e \in E_{ips}} X_{sje}(ip) \ge M_j \qquad \forall j \tag{17}$$

$$\sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{e \in E_{ips}} t_{sj}(ip) X_{sje}(ip) \le b_j M_j \qquad \forall j \tag{18}$$

$$X_{sje}(ip) + X_{(s+1)\hat{j}\hat{e}}(ip) - 2 L_{sj\hat{j}e\hat{e}}(ip) \ge 0 \qquad \forall i, p, s \in \{1, 2, \ldots, S(ip) - 1\}, \tag{19}$$

$$e \in E_{ips}, \hat{e} \in E_{ip(s+1)}, j \in J_{ips}, \hat{j} \in J_{ip(s+1)}$$

$$X_{sje}(ip) + X_{(s+1)\hat{j}\hat{e}}(ip) - L_{sj\hat{j}e\hat{e}}(ip) \le 1 \qquad \forall i, p, s \in \{1,2,\ldots,S(ip)-1, \quad (20)$$

$$e \in E_{ips}, \hat{e} \in E_{ip(s+1)}, j \in J_{ips}, \hat{j} \in J_{ip(s+1)}$$

$$[L_{sj\hat{j}e\hat{e}}(ip), X_{sje}(ip), Z(ip), Y_{se}(ip), M_j] \in \{0,1\} \qquad \forall i, p, s, e \in E_{ips}, \hat{e} \in E_{ip(s+1)}, \quad (21)$$

$$j \in J_{ips}, \hat{j} \in J_{ip(s+1)}$$

The assignments determined by the model (i.e. the $X_{sje}(ip)$) are then summarized in the matrix $A_{sj}(ip)$ in which the element $a_{sj}(ip)$ is equal to one if operations s of (ip) is to be performed at machine j, and otherwise zero. The matrix $A_{sj}(ip)$ now carries the index p, in anticipation of the fact that with each iteration, the operation allocation model might select a different process plan for a part type. Each process plan will have a different set of operations, which might require different material handling operation/sub-operation combinations and therefore different material handling requirements. The matrix $A_{sj}(ip)$ passes on this information to the material handling systems selection model.

3.2. Sub-model 2. Material Handling System Selection

The material handling system selection model is essentially the same as the one developed by Paulo, et al. (1999). However, the decision variables were modified to include the index p of process plan for each part type. The notation was also modified to accommodate the interfacing of this model with the operation allocation model.

The new implementation of the 0-1 integer programming model is developed below.

3.2.1. Mathematical Formulation

As assumed in the operation allocation model, the same set of n part types were considered; they are labeled with the indices $i = 1, ..., n$, where the part type i has the known and uniform demand d_i over the planning period. A part type i can be described in terms of five key product variables that define the choices of manufacturing technology associated with its conception, realization, disposition and disposal. These are labeled by indices $t = 1, \ldots, T(i)$. In our case $T(i) = 5$ and the key product variables are complexity, precision, lot or batch size, diversity and mass or linear dimension (Ayres, 1988). The set of m machines is described by the indices $j = 1, ..., m$. At these machines, the required manufacturing operations of (ip) are represented by the indices $s = 1, ..., S(ip)$.

The major material handling operations, $h = 1, ..., H$, where in our case $H = 5$, are given as load/unload, transportation between manufacturing processes, handling/rehandling away from the workplace, inspection and storage and retrieval. Each such operation is associated with a number of sub-operations labeled as $\hat{h} = 1, ..., \hat{H}$, where in our case $\hat{H} = 6$. These are orientation change, position change, quantity change, sequence change, timing change and no change (Paulo, 2000). A number of material handling devices are available to perform these material handling operation/sub-operation combinations. These are labeled as $e = 1, ..., E$.

The 0-1 decision variables are denoted by $Y_{h\hat{h}ejs}(ip)$, where $Y_{h\hat{h}ejs}(ip) = 1$ if $(h\hat{h})$ requires material handling equipment e at machine j where manufacturing operation s of (ip) is performed.

The objective is to generate the optimal material handling selection for a given mix of part types based on the part/process combinations and the choices of material handling equipment available. Thus, the objective function is to maximize (Paulo, 2000):

$$\sum_{e=1}^{E}\sum_{h=1}^{H}\sum_{\hat{h}=1}^{\hat{H}} W_{h\hat{h}e} \sum_{i=1}^{n} C_{ei} \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{j \in J_{ipe}} A_{sj}(ip)\,\alpha_{h\hat{h}sjip}\,Y_{h\hat{h}ejs}(ip) \qquad (22)$$

where

$$C_{ei} = 1 - \frac{\sum_{t=1}^{T=5} \left| W_{et} - \hat{W}_{it} \right|}{5T}$$

Here $W_{h\hat{h}e}$ is a measure of the ability of a piece of material handling equipment to handle a certain operation/sub-operation combination, while W_{et} and $\hat{W}_{it}$ relate the key product variables to the material handling equipment and the part type, respectively.

The parameter C_{ei}, as proposed by Paulo (2000), is a measure of the compatibility of a piece of equipment and a part type. This parameter evaluates C_{ei} to a number between 0 and 1, where 0 indicates incompatibility and 1 indicates complete compatibility. Incompatibility would occur for a situation where the values of W_{et} and $\hat{W}_{it}$ are as far apart as possible, which signals that the material handling equipment is unsuitable to handle that part type. For most situations, the parameter C_{ei} evaluates to a numerical value between 0 and 1, indicating some degree of compatibility.

Integer scales are used to assign values to the W parameters. The rating scales range from 0 to 5 for W_{et} and $W_{h\hat{h}e}$ and 1 to 5 for $\hat{W}_{it}$. The interpretations of the values are given in Tables 1,2 and 3.

Table 1. Rating Scale for W_{Mc} (Paulo, 2000)

Rating	Explanation
5	**Excellent** at performing the operation/sub-operation combination
4	**Very capable** of performing the operation/sub-operation combination
3	**Satisfactorily capable** of performing the operation/sub-operation combination
2	**Poor, but capable** of performing the operation/sub-operation combination
1	**Very poor, but minimally capable** at performing the operation/sub-operation combination
0	**Incapable** of performing the operation/sub-operation combination

Table 2. Rating Scale for W_{et} (Paulo, 2000)

Rating	Explanation
5	Piece of equipment best suited to handle parts with a very **high** rating of product variable t
4	Piece of equipment best suited to handle parts with a **high** rating of product variable t
3	Piece of equipment best suited to handle parts with a **moderate** rating of product variable t
2	Piece of equipment best suited to handle parts with a **low** rating of product variable t
1	Piece of equipment best suited to handle parts with a very **low** rating of product variable t
0	**Do not allow this** piece of equipment to handle parts with product variable t

Table 3. Rating Scale for $\hat{W}_{kt}$ (Paulo, 2000)

Rating	Explanation
5	Part type exhibits a very **high** level of the key product variable t
4	Part type exhibits a **high** level of the key product variable t
3	Part type exhibits a **moderate** level of the key product variable t
2	Part type exhibits a **low** level of the key product variable t
1	Part type exhibits a very **low** level of the key product variable t

The three rating factors ($W_{h\hat{h}e}$, W_{et} and $\hat{W}_{it}$) are largely subjective. Details of the quantification of the key product variables are given by Ayres (1988).

The matrix $A_{sj}(ip)$ is the output from the operation allocation model where any element from that matrix equals one if a manufacturing operation s of (ip) is performed at machine j and zero otherwise. This parameter is a link between the operation allocation model and the material handling system selection model, providing a necessary input to the material handling system selection model by describing the manufacturing operation assignments for each part type i.

The parameter $\alpha_{h\hat{h}sjip}$ equals one if material handling operation-sub operation combination $(h\hat{h})$ is required at machine j where manufacturing operation s of (ip) is performed, and zero otherwise. This parameter was also modified from its original definition by Paulo (2000) to include the index p for the reasons that were explained at the end of section 3.1.1.

The first set of constraints ensures that only one type of material handling equipment is chosen to perform the material handling operation/sub-operation combination associated with operation s of (ip) at machine j. It is expressed as:

$$\sum_{e \in E_{ips}} Y_{h\hat{h}ejs}(ip) = A_{sj}(ip)\alpha_{h\hat{h}sjip} \qquad \forall s,(ip),j,h,\hat{h} \qquad (23)$$

The next set of constraints ensures that a piece of equipment e is only chosen after another piece of equipment $\hat{e}$ has been assigned. This set of constraints is provided to allow precedence relationships that may exist in the assignment of material handling equipment. It is given as:

$$D_e \leq D_{\hat{e}} \qquad \forall e, \hat{e} \qquad (24)$$

where, $D_e = 1$ if a piece of equipment *e* has been chosen and zero otherwise. Similarly for $D_{\hat{e}}$.

The third set of constraints ensures that if a piece of material handling equipment is chosen, then at least one material handling operation/sub-operation combination must be performed by that equipment. It is mathematically expressed as:

$$\sum_{i=1}^{n}\sum_{h=1}^{H}\sum_{\hat{h}=1}^{\hat{H}}\sum_{p=1}^{P(i)}\sum_{s=1}^{S(ip)}\sum_{j\in J_{ips}} A_{sj}(ip)\alpha_{h\hat{h}sjip}Y_{h\hat{h}ejs}(ip) \geq D_e \qquad \forall e \qquad (25)$$

The last set of constraints ensures that the total time for all the jobs assigned to a piece of material handling equipment does not exceed the time available on that piece of equipment. It is given by:

$$\sum_{i=1}^{n} d_i \sum_{h=1}^{H}\sum_{\hat{h}=1}^{\hat{H}}\sum_{p=1}^{P(i)}\sum_{s=1}^{S(ip)}\sum_{j\in J_{ips}} t_{h\hat{h}e} A_{sj}(ip)\alpha_{h\hat{h}sjip}Y_{h\hat{h}ejs}(ip) \leq T_e D_e \qquad \forall e \qquad (26)$$

where $t_{h\hat{h}e}$ is the time required by material handling equipment *e* to perform the material handling operation/sub-operation combination $h\hat{h}$ and T_e is the time available on the material handling equipment *e*.

Assembling the above, we get the following complete statement of our 0-1 mathematical programming model of the material handling system selection model, which is designated as P (MH).

P (MH): Maximize

$$\sum_{e=1}^{E}\sum_{h=1}^{H}\sum_{\hat{h}=1}^{\hat{H}} W_{h\hat{h}e} \sum_{i=1}^{n} C_{ei} \sum_{p=1}^{P(i)}\sum_{s=1}^{S(ip)}\sum_{j\in J_{ips}} A_{sj}(ip)\,\alpha_{h\hat{h}sjip}\,Y_{h\hat{h}ejs}(ip) \tag{27}$$

where,

$$C_{ei} = 1 - \frac{\sum_{t=1}^{T=5}\left|W_{et} - \hat{W}_{it}\right|}{5T} \tag{28}$$

Subject to

$$\sum_{e\in E_{ips}} Y_{h\hat{h}ejs}(ip) = A_{sj}(ip)\,\alpha_{h\hat{h}sjip} \qquad \forall s,(ip),j,h,\hat{h} \tag{29}$$

$$D_e \le D_{\hat{e}} \qquad \forall e,\hat{e} \tag{30}$$

$$\sum_{i=1}^{n}\sum_{h=1}^{H}\sum_{\hat{h}=1}^{\hat{H}}\sum_{p=1}^{P(i)}\sum_{s=1}^{S(ip)}\sum_{j\in J_{ips}} A_{sj}(ip)\,\alpha_{h\hat{h}sjip}\,Y_{h\hat{h}ejs}(ip) \ge D_e \qquad \forall e \tag{31}$$

$$\sum_{i=1}^{n} d_i \sum_{h=1}^{H}\sum_{\hat{h}=1}^{\hat{H}}\sum_{p=1}^{P(i)}\sum_{s=1}^{S(ip)}\sum_{j\in J_{ips}} t_{h\hat{h}e}\,A_{sj}(ip)\,\alpha_{h\hat{h}sjip}\,Y_{h\hat{h}ejs}(ip) \le T_e . D_e \qquad \forall e \tag{32}$$

$$[Y_{h\hat{h}ejs}(ip), D_e, D_{\hat{e}}] \in \{0,1\} \qquad \forall i,p,s,h,\hat{h},e,j\in J_{ips} \tag{33}$$

The assignments determined by the model (i.e. the $Y_{h\hat{h}ejs}(ip)$) are then summarized in the matrix $B_{sje}(ip)$ in which the element $b_{sje}(ip)$ is equal to one if operations *s* of *(ip)* is performed at machine *j*, using material handling equipment *e* to transport the part to the next machine and zero otherwise. The matrix B provides the necessary information about the assignment of the material handling equipment to various operations of *(ip)* so as to enable the P (OA) model to compute the material handling costs in its objective function. The output matrix $B_{sje}(ip)$ from the P (MH) model helps to reduce the choices of material handling equipment from E_{ips} in the next iteration. This allocates one material handling equipment *e* to any (*ip*), for operation *s* to be performed on machine *j* thus forcing the model to select a material handling equipment. The matrix $B_{sje}(ip)$ forms the feedback link between P (MH) and P (OA), thus completing the feedback loop.

3.3. Justification: Cost of Transportation Material Handling Operation

In the present work only the transportation component of the major material handling operations is included in the cost calculations. In P (MH), five major material handling operations were considered namely, load/unload, transportation between manufacturing processes, handling/rehandling, inspection and storage and retrieval. However, for the purpose of this research, only the transportation coat is included in P (OA). This is justifiable due to the reasons as discussed below.

1. Transportation cost is a major component of the total material handling costs. Hence, the effect of the other material handling operations costs on the final solution will be minimal.
2. When compared to other material handling operations, transportation component can be easily measured. For example, it becomes difficult to quantify load/unload or handling/rehandling material handling operation, whereas transportation cost can be calculated in terms of distances traveled or times taken for the journey.

3. On a shop floor, transportation component is the highly variable material handling operation compared to other operations such as load/unload operations, which are fairly constant for all part types and machines. There are some exceptions to this assumption, but by and large it holds up in many situations.

3.4. Algorithm to Solve the Two Models Iteratively

The following algorithm has been developed to solve the two models iteratively.

Step 1. Solve the model P (OA) and develop the matrix $A_{sj}(ip)$ from $X_{sje}(ip)$.

Step 2. Using $A_{sj}(ip)$, solve the model P (MH) and develop the matrix $B_{sje}(ip)$ from $Y_{h\hat{h}jes}(ip)$

Step 3. For each e in $B_{sje}(ip)$ if $e \in E_{ips}$ then remove all elements in E_{ips} except e, and denote the new set as $\hat{E}_{ips} = \{e\}$ where $\hat{E}_{ips} = E_{ips}$.

Step 4. Set $\hat{E}_{ips} = E_{ips}$ and go to step 1 and repeat until the solution converges. In other words, stop the iterations when $X^{k+1}{}_{sje}(ip) = X^{k}{}_{sje}(ip)$ and $Y^{k+1}{}_{h\hat{h}jes}(ip) = Y^{k}{}_{h\hat{h}jes}(ip)$, where k is the number of iterations.

CHAPTER 4. A NUMERICAL EXAMPLE

An example is presented to demonstrate the viability of this work and of the models developed. This small randomly generated example is partially based on the work of Paulo (2000) and was solved using LINGO (Lindo Systems Inc., 1999). The LINGO program files that were produced to solve this example can be found in Appendix I.

4.1. The Operation Allocation Problem

To solve the operation allocation problem, assume that we have $i = 1,\dots, 6$ part types to be manufactured with demands as listed in Table 4. The part types have P(1) = 2, P(2) = 3, P(3) = 2, P(4) = 2, P(5) = 3, P(6) = 1 different process plans, each characterized by a number of manufacturing operations. There are $j = 1,\dots, 5$ machines with known capacities $b_j = 57600$ time units, and setup costs as listed in Table 4. Each machine is capable of performing certain operations required by the process plans. There are $e = 1,\dots, 7$ different types of material handling equipment available. However, only equipment $e = 3,4,5,7$ are used to transport part types from one machine to another. For example: under process plan $p = 1$, part type $i = 1$ has S (11) = 3 operations with indices $s \in \{1,2,3\}$. Operation $s = 1$of process plan $p = 1$, part type 1 can be completed on any of the machines $j \in J_{111} = \{1,3,4\}$; for $j \in J_{111} = \{1,3,4\}$ MH equipment available for transportation are $e = \{3,4,5,7\}$. Operation $s = 2$ can be completed on any of the machines $j \in J_{112} = \{2,5\}$; for $j \in J_{112} = \{2,5\}$ MH equipment available for transportation are $e = \{3,4,5,7\}$. Operation $s = 3$ can be completed on any of the machines $j \in J_{113} = \{3,4\}$; for

$j \in J_{113}$ = {3,4} MH equipment available for transportation are e = {3,4,5,7}. The information for all allowable combinations (ip) are summarized in Table 4, which contains the values of the operation times $t_{sj}(ip)$ and costs $OC_{sj}(ip)$. The information about the transportation cost $T_{iejj'}$ for each part type, from machine j to machine j' for various MH equipment e is given in Tables 5.1 through 5.24.

4.2. The Material Handling System Selection Problem

As discussed previously, it is assumed that each product has t =1,...,5 choices of manufacturing technologies, which describe the part types in terms of their key product variables as seen in Table 6.

If we analyze one of the part types from Table 6 we observe that part type i = 2 has a high degree of complexity and precision. In other words, this part type is composed of a large number of geometrical and dimensional features and it must be manufactured to close tolerances. The very low value for diversity indicates that this part belongs to a part family composed of a small number of products. We also know that this part is manufactured in medium-size batches and it is large in dimension/mass. A similar description of each part type can be inferred from Table 6.

The major material handling operations h = 1,..., 5, are load/unload, handling/rehandling, transportation, inspection and storage/ retrieval. Each of these operations is associated with one or more sub-operations such as orientations, positioning, quantity, sequence, timing or "none". These are labeled with the indices $\hat{h}$ = 1,...,6. For this example it is

Table 4: Manufacturing operations times $t_{ij}(ip)$ and costs $OC_{ij}(ip)$, part type demands d_i and machine set up costs SC_j.

	Part types, *i*																	
	1					2							3					
	Process Plan, *p*					Process Plan, *p*							Process Plan, *p*					
	1			2		1		2			3		1		2			
Machine, *j*	1	2	3	1	2	1	2	1	2	3	1	2	1	2	1	2	3	4
1	6 $9				4 $6	6 $9				4 $6		6 $9		11 $17		2 $3		10 $15
2		12 $18		6 $8			11 $22	7 $9			4 $5			7 $7	7 $9			10 $8
3	11 $8		12 $9	9 $7		8 $6				12 $12	8 $6			12 $9	4 $3		11 $11	
4	5 $10		10 $20		13 $26	13 $26			10 $20				2 $4		8 $16		2 $4	
5		11 $11			11 $11		11 $11		8 $8				11 $11			11 $22		
Demand, d_i	30					50							45					

Table 4. (Cont'd 1)

	Part types, *i*																
	4					5							6				M/c set up cost
	Process Plan, *p*					Process Plan, *p*							Process Plan, *p*				
	1			2		1			2		3		1				SC_j
Machine, *j*	1	2	3	1	2	1	2	3	1	2	1	2	1	2	3	4	
1		7 $11		6 $9		4 $6		13 $20		2 $3		2 $3	5 $8			3 $5	$120
2			9 $11		11 $14		2 $3			8 $10			6 $8			3 $4	$230
3		8 $16		12 $9			4 $3		6 $5			13 $26	10 $8				$450
4	10 $20		9 $9	2 $4				13 $16	2 $4		8 $8				4 $8		$60
5	7 $7				11 $11	13 $13		9 $7				7 $7		7 $9		7 $7	$180
Demand, d_i	65					25							40				

Tables 5.1 through 5.24. Cost of moving a unit of part type i from machine j to $\hat{j}$ using material handling equipment e, $T_{iej\hat{j}}$ (Only MH Equipment available for transportation are considered)

MH equipment 3 (Forklift truck)

Part type 1

j \ $\hat{j}$ M/c	1	2	3	4	5
1	0	6	9	12	8
2	6	0	6	11	8
3	9	6	0	6	11
4	12	11	6	0	9
5	8	8	11	9	0

Part type 2

j \ $\hat{j}$ M/c	1	2	3	4	5
1	0	10	15	20	13
2	10	0	10	18	13
3	15	10	0	10	18
4	20	18	10	0	15
5	13	13	18	15	0

Part type 3

j \ $\hat{j}$ M/c	1	2	3	4	5
1	0	12	15	18	14
2	12	0	12	17	14
3	15	12	0	12	17
4	18	17	12	0	15
5	14	14	17	15	0

Part type 4

j \ $\hat{j}$ M/c	1	2	3	4	5
1	0	10	13	16	12
2	10	0	10	15	12
3	13	10	0	10	15
4	16	15	10	0	13
5	12	12	15	13	0

Part type 5

j \ $\hat{j}$ M/c	1	2	3	4	5
1	0	8	11	14	10
2	8	0	8	13	10
3	11	8	0	8	13
4	14	13	8	0	11
5	10	10	13	11	0

Part type 6

j \ $\hat{j}$ M/c	1	2	3	4	5
1	0	13	16	19	15
2	13	0	13	18	15
3	16	13	0	13	18
4	19	18	13	0	16
5	15	15	18	16	0

MH equipment 4 (Belt conveyor)

Part type 1

j \ $\hat{j}$ M/c	1	2	3	4	5
1	0	7	21	14	9
2	7	0	7	13	9
3	21	7	0	7	13
4	14	13	7	0	11
5	9	9	13	11	0

Part type 2

j \ $\hat{j}$ M/c	1	2	3	4	5
1	0	12	18	24	15
2	12	0	12	21	15
3	18	12	0	12	21
4	24	21	12	0	18
5	15	15	21	18	0

Part type 3

j \ $\hat{j}$ M/c	1	2	3	4	5
1	0	13	27	20	15
2	13	0	13	19	15
3	27	13	0	13	19
4	20	19	13	0	17
5	15	15	19	17	0

Part type 4

j \ $\hat{j}$ M/c	1	2	3	4	5
1	0	11	25	18	13
2	11	0	11	17	13
3	25	11	0	11	17
4	18	17	11	0	15
5	13	13	17	15	0

Part type 5

j \ $\hat{j}$ M/c	1	2	3	4	5
1	0	9	23	16	11
2	9	0	9	15	11
3	23	9	0	9	15
4	16	15	9	0	13
5	11	11	15	13	0

Part type 6

j \ $\hat{j}$ M/c	1	2	3	4	5
1	0	14	18	21	16
2	14	0	14	20	16
3	18	14	0	14	19
4	21	20	14	0	18
5	16	16	19	18	0

Table 5. (Cont'd 1)

MH equipment 5 (AGV)

Part type 1

		j				
	M/c	1	2	3	4	5
	1	0	10	15	20	13
	2	10	0	10	18	18
i	3	15	10	0	10	18
	4	20	18	10	0	15
	5	13	18	18	15	0

Part type 2

	j				
M/c	1	2	3	4	5
1	0	18	27	36	23
2	18	0	18	32	23
3	27	18	0	18	32
4	36	32	18	0	28
5	23	23	32	28	0

Part type 3

	j				
M/c	1	2	3	4	5
1	0	18	23	28	21
2	18	0	18	26	26
3	23	18	0	18	26
4	28	26	28	0	23
5	21	26	26	23	0

Part type 4

		j				
	M/c	1	2	3	4	5
	1	0	16	21	26	19
	2	16	0	16	24	24
i	3	21	16	0	16	24
	4	26	24	16	0	21
	5	19	24	24	21	0

Part type 5

	j				
M/c	1	2	3	4	5
1	0	14	19	24	17
2	14	0	14	22	22
3	19	14	0	14	22
4	24	22	14	0	19
5	17	22	22	19	0

Part type 6

	j				
M/c	1	2	3	4	5
1	0	19	24	29	22
2	19	0	19	27	27
3	24	19	0	19	27
4	19	27	19	0	24
5	22	27	27	24	0

MH equipment 7 (Powered hand truck)

Part type 1

		j				
	M/c	1	2	3	4	5
	1	0	9	14	18	11
	2	9	0	9	16	11
i	3	14	9	0	9	16
	4	18	16	9	0	14
	5	11	11	16	14	0

Part type 2

	j				
M/c	1	2	3	4	5
1	0	16	24	32	20
2	16	0	16	28	20
3	24	16	0	16	28
4	32	28	16	0	24
5	20	20	28	24	0

Part type 3

	j				
M/c	1	2	3	4	5
1	0	15	20	24	18
2	15	0	15	22	17
3	20	15	0	15	22
4	24	22	15	0	20
5	18	18	22	20	0

Part type 4

		j				
	M/c	1	2	3	4	5
	1	0	13	18	22	15
	2	13	0	13	20	15
i	3	18	13	0	13	20
	4	22	20	13	0	18
	5	15	15	20	18	0

Part type 5

	j				
M/c	1	2	3	4	5
1	0	11	16	20	13
2	11	0	11	18	13
3	16	11	0	11	18
4	20	18	11	0	16
5	13	13	18	16	0

Part type 6

	j				
M/c	1	2	3	4	5
1	0	16	21	25	19
2	16	0	16	23	18
3	21	16	0	16	23
4	25	23	16	0	21
5	19	18	23	21	0

assumed that we have $e = 1, \ldots, 7$ different types of material handling equipment. Each of these is available for 57600 time units. The material handling equipment is rated against the choices of manufacturing technology as seen in Table 7. If we analyze the MH equipment from Table 7 we observe that, for example, the available fork lift truck is best suited to handle part types with a low degree of complexity and precision, a high degree of diversity, large batch sizes and very high mass/linear dimension. In other words, the ideal part type for the fork lift truck to handle is one that is described by a small number of geometrical and dimensional features, does not requires very high tolerances, belongs to a part family with a high number of members and is produced in large batches.

The material handling equipment is also rated on its ability to perform the various material handling operation/sub-operation combinations (Table 8). Again, using forklift truck as an example, we can see that this equipment is capable of performing the various operations required for transportation. The degree to which these equipment is able to perform the various operation/sub-operation combinations varies. For example, forklift truck is incapable of performing load/unload operations, because these devices are designed to transport the parts.

The unit times required by the various types of material handling equipment to perform the material handling operation/sub-operation combinations are given in Table 9.

The material handling requirements are derived from the operation allocation model data, and are summarized in Table 10. The availability of the material handling equipment for transportation operation is also given in Table 10.

Table 6. $\mathring{W}_{ik}$ table for the case study example.

Part, *i*	Complexity	Precision	Diversity	Batch size	Mass/Linear Dimension
1	2	2	3	2	2
2	5	5	1	3	4
3	3	3	1	2	3
4	4	2	2	4	4
5	2	3	4	1	3
6	3	2	1	2	2

Table 7. W_{et} table for the case study example.

	Equipment, *e*	Complexity	Precision	Diversity	Batch size	Mass/Linear Dimension
1	Robot	4	4	2	4	1
2	Human	5	4	4	2	2
3	Fork lift truck	1	1	4	4	5
4	Belt conveyor	2	2	4	3	2
5	AGV	4	4	1	1	2
6	AS/RS	4	4	5	3	3
7	Powered hand truck	1	1	4	3	3

Table 8. W_{hle} **values for the example.**

	(un)Load						(re)Handling						Transportation						Inspection						Storage/Retrieval					
Equipment, *e*	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N
Robot	5	5	2	5	5	5	5	5	2	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Human	5	5	5	5	4	5	5	5	5	5	4	5	0	0	0	0	0	0	5	5	5	5	4	5	0	0	0	0	0	0
Forklift Truck	0	0	0	0	0	0	0	0	0	0	0	0	2	5	4	4	3	5	0	0	0	0	0	0	0	0	0	0	0	0
Belt conveyor	0	0	0	0	0	0	0	0	0	0	0	0	1	3	4	4	4	5	1	3	4	4	4	5	0	0	0	0	0	0
AGV	0	0	0	0	0	0	0	0	0	0	0	0	2	3	2	5	5	5	2	3	2	5	5	5	0	0	0	0	0	0
AS/RS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5
Powered hand truck	0	0	0	0	0	0	0	0	0	0	0	0	2	5	4	4	3	5	0	0	0	0	0	0	0	0	0	0	0	0

Table 9. t_{hle} **values for the example.**

	(un)Load						(re)Handling						Transportation						Inspection						Storage/Retrieval					
Equipment, *e*	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N
Robot	0.3	0.3	2.0	0.3	0.3	0.2	0.3	0.3	0.2	0.3	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Human	0.3	0.3	2.0	0.3	0.3	0.2	0.3	0.3	0.2	0.3	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
Forklift Truck	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Belt conveyor	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0
AGV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
AS/RS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	1.5	1.5	1.5	1.5	1.5
Powered hand truck	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 10. Material handling requirements, α_{hisjp} (material handling equipment available for different MH operations)

				(un)Load						(re)Handling						Transportation						Inspection						S/R					
Part, *i*	Plan, *p*	Mfg Opn. *s*	M/c, *j*	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N
1	1	1	1						*												*												
			3						*												*												
			4	*																	*												
		2	2		*																*												
			5						*								*																
		3	3		*																*									*			
			4						*												*									*			
	2	1	2		*																*												
			3						*												*												
		2	1	*																	*							*					
			4						*												*												*
			5		*																*												*
2	1	1	1	*																	*												
			3		*																*												
			4						*												*												
		2	2	*													*											*					
			5						*			*									*									*			
	2	1	2		*																*												
		2	4						*												*												
			5	*													*																
		3	1		*																*									*			
			3						*												*									*			
	3	1	2		*																*												
			3	*																	*												
		2	1		*												*												*				
3	1	1	4	*																	*												
			5						*								*																
		2	1		*																*							*					
			2						*								*											*					
			3	*																	*									*			
Available MH Equipment				1,2						1,2						3,4,5,7						2,4,5						6					

Table 10. (cont'd 1)

				(un)Load						(re)Handling						Transportation						Inspection						S/R					
Part, *i*	Plan, *p*	Mfg Opn. *s*	M/c, *j*	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N
3	2	1	2		•																•												
			3		•																•												
			4	•																	•												
		2	1		•																•												
			5	•																	•												
		3	3						•								•																
			4		•																•												
		4	1		•																•												•
			2	•																	•									•			
4	1	1	4		•													•															
			5	•												•																	
		2	1						•			•									•												•
			3		•													•						•						•			
	2	1	2	•																	•												
			5	•												•																	
		2	1						•									•															
			3	•								•									•												
			4		•													•						•									
		3	2	•																	•							•					
			5						•												•									•			
5	1	1	1						•												•												
			5	•																	•												
		2	2						•									•															
			3	•								•				•																	
		3	1						•						•						•							•					
			4		•																•												•
			5						•									•												•			
Available MH Equipment				1,2						1,2						3,4,5,7						2,4,5						6					

Table 10. (cont'd 2)

				(un)Load						(re)Handling						Transportation						Inspection						S/R					
Part, i	Plan, p	Mfg Opn. s	M/c, j	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N	O	P	Q	S	T	N
5	2	1	3	•											•						•												
			4						•			•						•															
		2	1	•																	•												•
			2		•							•									•												•
	3	1	4		•																•												
		2	1						•												•							•					
			3		•													•															•
			5	•																	•							•					
6	1	1	1		•													•															
			2	•																	•												
			3						•												•												
		2	5		•																•												
		3	4						•		•										•												
		4	1	•														•															•
			2		•						•										•							•					
			5						•		•							•						•						•			
Available MH Equipment				1,2						1,2						3,4,5,7						2,4,5						6					

4.3. Solution to the Numerical Example

The two models were solved using the algorithm in section 3.4. First, the P (OA) model was solved, and the results from the first iteration were summarized in Table 11. The first iteration solution includes the minimum total cost including transportation cost irrespective of the compatibility of the material handling equipment to be used for a part type. In other words, in the first iteration the model P (OA) does not use any information from the model P (MH). The operation, machine setup and transportation costs corresponding to the first iteration are given in Table 12.

The results indicate that machines 1,2,4 and 5 were selected to process part types $i = 1,\ldots, 6$ under one of their possible 7process plans using one of the material handling equipment to transport the part type. For example, operation 1 of part type 1, under plan type 2, is processed on machine 2 and material handling equipment 3 is used to transport the part type from machine 2 to machine 1 for the second operation. From Table 11, the matrix $A_{sj}(ip)$ can be derived which serves as the input to the P (MH) above model. Next, the P (MH) model was solved and the results from the first iteration are summarized in Table 13. The objective function value, (i.e., the compatibility index) is 134.35. The allocations (decision variables, $Y_{hfejs}(ip)$) for the material handling equipment for the $A_{sj}(ip)$ are given in Table 14. For example, part type 1, under process plan 2, on machine 2 for operation 1 requires human to (un)Load the part type, and conveyor for transporting the part to the next machine. The information about the material handling equipment for transportation operation is required for the next iteration of the P (OA) model and is, therefore, summarized from Table 14 in the matrix $B_{sje}(ip)$ (Table 13).

Table 11. Solution of the operation allocation model, $X_{sjk}(ip)$ from the first iteration

Part, *i*	Process Plan, *p*	Operation, *s*	Machine, *j*	MH Equipment, *e*
1	2	1	2	3
		2	1	3
2	3	1	2	3
		2	1	7
3	1	1	4	4
		2	2	4
4	1	1	5	3
		2	1	7
5	2	1	4	7
		2	2	4
6	1	1	1	5
		2	5	3
		3	4	3
		4	2	7

Table 12: Different costs for the $X_{sjk}(ip)$ assignments from the first iteration

Operation cost	4295
M/c Set up cost	590
Transportation cost	2105
Total cost	6990

Table 13. $B_{sjk}(ip)$ Matrix summarized from the P (MH) model, from the first iteration.

Part, *i*	Process Plan, *p*	Operation, *s*	Machine, *j*	MH Equipment, *e*
1	2	1	2	4
		2	1	4
2	3	1	2	5
		2	1	5
3	1	1	4	5
		2	2	7
4	1	1	5	3
		2	1	3
5	2	1	4	4
		2	2	4
6	1	1	1	4
		2	5	5
		3	4	5
		4	2	5

Table 14. Solution to the material handling system selection problem $Y_{Mks}(ip)$. (First iteration)

Part type 1				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
2	1	2	(un)Load/Position	Human
			Transportation/None	Conveyor
	2	1	(un)Load/Orientation	Human
			Transportation/None	Conveyor
			S&R/Orientation	AS/RS

Part type 2				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
3	1	2	(un)Load/Position	Human
			Transportation/None	AGV
	2	1	(un)Load/Position	Human
			Transportation/Position	AGV
			S&R/Position	AS/RS

Part type 3				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
1	1	4	(un)Load/Orientation	Human
			Transportation/None	AGV
	2	2	(un)Load/None	Human
			Transportation/Position	Powered Hand truck
			S&R/Orientation	AS/RS

Part type 4				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
1	1	5	(un)Load/Orientation	Robot
			Transportation/Orientation	Forklift truck
	2	1	(un)Load/None	Robot
			Handling/Quantity	Human
			Transportation/None	Forklift truck
			S&R/None	AS/RS

Part type 5				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
2	1	4	(un)Load/None	Human
			Handling/Quantity	Human
			Transportation/Quantity	Conveyor
	2	2	(un)Load/Position	Human
			(re)Handling/Quantity	Human
			Transportation/None	Conveyor
			S&R/None	AS/RS

Part type 6				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
1	1	1	(un)Load/Position	Human
			Transportation/Quantity	Conveyor
	2	5	(un)Load/Position	Human
			Transportation/None	AGV
	3	4	(un)Load/None	Human
			(re)Handling/Position	Human
			Transportation/None	AGV
	4	2	(un)Load/Position	Human
			(re)Handling/Position	Human
			Transportation/None	AGV
			S&R/Orientation	AS/RS

Using the information from matrix $B_{sje}(ip)$, all other choices of material handling equipment for the transportation of (ip) combinations to perform operation s on machine j were eliminated from E_{ips}. The model P (OA) now seeks to find a new set of optimal decision variables, $X_{sje}(ip)$, under the current conditions. In the next iteration, the new allocations are passed on to the model P (MH), to compute the next iteration and the process continues. The results of the second, third and fourth iterations are shown in Tables 15-34, respectively and the corresponding values of the objective functions are summarized in Table 35.

Note that, in the first iteration, the objective function value of P (OA) is low relative to subsequent iterations. This is due to the fact that, in the first iteration, P (OA) chooses minimal cost material handling equipment irrespective of the compatibility of the part types with the equipment. Afterwards, as the consideration for part type- MH equipment compatibility enters the optimization process, P (OA) is forced to choose equipment with higher compatibility indices, which are more expensive.

Table 15. Solution of the operation allocation model, $X_{sje}(ip)$ from the second iteration

Part, *i*	Process Plan, *p*	Operation, *s*	Machine, *j*	MH Equipment, *e*
1	2	1	2	4
		2	1	4
2	3	1	2	5
		2	1	5
3	1	1	4	5
		2	3	4
4	1	1	5	3
		2	1	3
5	2	1	3	7
		2	1	5
6	1	1	3	4
		2	5	5
		3	4	5
		4	1	4

Table 16: Different costs for the $X_{sje}(ip)$ assignments from the second iteration

Operation cost	4275
M/c Set up cost	1040
Transportation cost	2835
Total cost	8150

Table 17. $B_{sje}(ip)$ Matrix summarized from the P (MH) model, from the second iteration.

Part, *i*	Process Plan, *p*	Operation, *s*	Machine, *j*	MH Equipment, *e*
1	2	1	2	4
		2	1	4
2	3	1	2	5
		2	1	5
3	1	1	4	5
		2	3	5
4	1	1	5	3
		2	1	3
5	2	1	3	4
		2	1	4
6	1	1	3	5
		2	5	5
		3	4	5
		4	1	4

Table 18. Solution to the material handling system selection problem $Y_{hjkz}(ip)$. (Second iteration)

Part type 1				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
2	1	2	(un)Load/Position	Human
			Transportation/None	Conveyor
	2	1	(un)Load/Orientation	Human
			Transportation/None	Conveyor
			S&R/Orientation	AS/RS

Part type 2				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
3	1	2	(un)Load/Position	Human
			Transportation/Position	AGV
	2	1	(un)Load/Position	Human
			Transportation/Position	AGV
			S&R/Position	AS/RS

Part type 3				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
1	1	4	(un)Load/Orientation	Human
			Transportation/None	AGV
	2	3	(un)Load/Orientation	Human
			Transportation/None	AGV
			S&R/Quantity	AS/RS

Part type 4				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
1	1	5	(un)Load/Orientation	Robot
			Transportation/Orientation	Forklift truck
	2	1	(un)Load/None	Robot
			Handling/Quantity	Human
			Transportation/None	Conveyor
			S&R/None	AS/RS

Part type 5				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
2	1	3	(un)Load/Orientation	Human
			Handling/None	Human
			Transportation/None	Conveyor
	2	1	(un)Load/Orientation	Human
			Transportation/None	Conveyor
			S&R/None	AS/RS

Part type 6				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
1	1	3	(un)Load/None	Human
			Transportation/None	AGV
	2	5	(un)Load/Position	Human
			Transportation/None	AGV
	3	4	(un)Load/None	Human
			(re)Handling/Position	Human
			Transportation/None	AGV
	4	1	(un)Load/Orientation	Human
			Transportation/Quantity	Conveyor
			S&R/None	AS/RS

Table 19. Solution of the operation allocation model, $X_{sje}(ip)$ from the third iteration

Part, *i*	Process Plan, *p*	Operation, *s*	Machine, *j*	MH Equipment, *e*
1	2	1	2	4
		2	1	4
2	3	1	2	5
		2	1	5
3	1	1	4	5
		2	2	7
4	1	1	5	3
		2	1	3
5	1	1	1	7
		2	2	5
		3	5	7
6	1	1	2	5
		2	5	5
		3	4	5
		4	1	4

Table 20: Different costs for the $X_{sje}(ip)$ assignments from the third iteration

Operation cost	4385
M/c Set up cost	590
Transportation cost	3665
Total cost	8640

Table 21. $B_{sje}(ip)$ Matrix summarized from the P (MH) model, from the third iteration.

Part, *i*	Process Plan, *p*	Operation, *s*	Machine, *j*	MH Equipment, *e*
1	2	1	2	4
		2	1	4
2	3	1	2	5
		2	1	5
3	1	1	4	5
		2	2	7
4	1	1	5	3
		2	1	3
5	1	1	1	4
		2	2	4
		3	5	7
6	1	1	2	5
		2	5	5
		3	4	5
		4	1	4

Table 22. Solution to the material handling system selection problem $Y_{Mj e s}(ip)$. (Third iteration)

Part type 1

Plan	Mfg Op	M/C	Material Handling op.	Equipment
2	1	2	(un)Load/Position	Human
			Transportation/None	Conveyor
	2	1	(un)Load/Orientation	Human
			Transportation/None	Conveyor
			S&R/Orientation	AS/RS

Part type 2

Plan	Mfg Op	M/C	Material Handling op.	Equipment
3	1	2	(un)Load/Position	Human
			Transportation/None	AGV
	2	1	(un)Load/Position	Human
			Transportation/Position	AGV
			S&R/Position	AS/RS

Part type 3

Plan	Mfg Op	M/C	Material Handling op.	Equipment
1	1	4	(un)Load/Orientation	Human
			Transportation/None	AGV
	2	2	(un)Load/none	Human
			Transportation/Position	Powered Hand Truck
			S&R/Orientation	AS/RS

Part type 4

Plan	Mfg Op	M/C	Material Handling op.	Equipment
1	1	5	(un)Load/Orientation	Robot
			Transportation/Orientation	Forklift truck
	2	1	(un)Load/None	Robot
			Handling/Quantity	Human
			Transportation/None	Forklift truck
			S&R/None	AS/RS

Part type 5

Plan	Mfg Op	M/C	Material Handling op.	Equipment
1	1	1	(un)Load/None	Human
			Transportation/None	Conveyor
	2	2	(un)Load/None	Human
			Transportation/Quantity	Conveyor
	3	5	(un)Load/None	Human
			Transportation/Position	Powered Hand Truck
			S&R/Orientation	AS/RS

Part type 6

Plan	Mfg Op	M/C	Material Handling op.	Equipment
1	1	2	(un)Load/Orientation	Human
			Transportation/None	AGV
	2	5	(un)Load/Position	Human
			Transportation/None	AGV
	3	4	(un)Load/None	Human
			(re)Handling/Position	Human
			Transportation/None	AGV
	4	1	(un)Load/Orientation	Human
			Transportation/Quantity	Conveyor
			S&R/None	AS/RS

Table 23. Solution of the operation allocation model, $X_{sje}(ip)$ from the fourth iteration

Part, *i*	Process Plan, *p*	Operation, *s*	Machine, *j*	MH Equipment, *e*
1	2	1	2	4
		2	1	4
2	3	1	2	5
		2	1	5
3	1	1	4	5
		2	2	7
4	1	1	5	3
		2	1	3
5	3	1	4	5
		2	1	7
6	1	1	2	5
		2	5	5
		3	4	5
		4	1	4

Table 24: Different costs for the $X_{sje}(ip)$ assignments from the fourth iteration

Operation cost	4260
M/c Set up cost	590
Transportation cost	3940
Total cost	8790

Table 25. $B_{sje}(ip)$ Matrix summarized from the P (MH) model, from the fourth iteration.

Part, *i*	Process Plan, *p*	Operation, *s*	Machine, *j*	MH Equipment, *e*
1	2	1	2	4
		2	1	4
2	3	1	2	5
		2	1	5
3	1	1	4	5
		2	2	7
4	1	1	5	3
		2	1	3
5	1	1	4	4
		2	1	4
6	1	1	2	5
		2	5	5
		3	4	5
		4	1	4

Table 26. Solution to the material handling system selection problem $Y_{kljcs}(ip)$. (Fourth iteration)

Part type 1

Plan	Mfg Op	M/C	Material Handling op.	Equipment
2	1	2	(un)Load/Position Transportation/None	Human Conveyor
	2	1	(un)Load/Orientation Transportation/None S&R/Orientation	Human Conveyor AS/RS

Part type 2

Plan	Mfg Op	M/C	Material Handling op.	Equipment
3	1	2	(un)Load/Position Transportation/None	Human AGV
	2	1	(un)Load/Position Transportation/Position S&R/Position	Human AGV AS/RS

Part type 3

Plan	Mfg Op	M/C	Material Handling op.	Equipment
1	1	4	(un)Load/Orientation Transportation/None	Human AGV
	2	2	(un)Load/None Transportation/Position S&R/Orientation	Human Powered Hand Truck AS/RS

Part type 4

Plan	Mfg Op	M/C	Material Handling op.	Equipment
1	1	5	(un)Load/Orientation Transportation/Orientation	Robot Forklift truck
	2	1	(un)Load/None Handling/Quantity Transportation/None S&R/None	Robot Human Forklift truck AS/RS

Part type 5

Plan	Mfg Op	M/C	Material Handling op.	Equipment
3	1	4	(un)Load/Position Transportation/none	Human Conveyor
	2	1	(un)Load/None Transportation/None S&R/Orientation	Human Conveyor AS/RS

Part type 6

Plan	Mfg Op	M/C	Material Handling op.	Equipment
1	1	2	(un)Load/Orientation Transportation/None	Human AGV
	2	5	(un)Load/Position Transportation/None	Human AGV
	3	4	(un)Load/None (re)Handling/Position Transportation/None	Human Human AGV
	4	1	(un)Load/Orientation Transportation/Quantity S&R/None	Human Conveyor AS/RS

Table 27. Solution of the operation allocation model, $X_{sje}(ip)$ from the fifth iteration

Part, *i*	Process Plan, *p*	Operation, *s*	Machine, *j*	MH Equipment, *e*
1	2	1	2	4
		2	1	4
2	3	1	2	5
		2	1	5
3	1	1	4	5
		2	2	7
4	1	1	5	3
		2	1	3
5	2	1	4	4
		2	1	4
6	1	1	2	5
		2	5	5
		3	4	5
		4	1	4

Table 28: Different costs for the $X_{sje}(ip)$ assignments from the fifth iteration

Operation cost	4160
M/c Set up cost	590
Transportation cost	4390
Total cost	9140

Table 29. $B_{sje}(ip)$ Matrix summarized from the P (MH) model, from the fifth iteration.

Part, *i*	Process Plan, *p*	Operation, *s*	Machine, *j*	MH Equipment, *e*
1	2	1	2	4
		2	1	4
2	3	1	2	5
		2	1	5
3	1	1	4	5
		2	2	7
4	1	1	5	3
		2	1	3
5	2	1	4	4
		2	1	4
6	1	1	2	5
		2	5	5
		3	4	5
		4	1	4

Table 30. Solution to the material handling system selection problem $Y_{Mjcs}(ip)$. (Fifth iteration)

Part type 1				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
2	1	2	(un)Load/Position	Human
			Transportation/None	Conveyor
	2	1	(un)Load/Orientation	Human
			Transportation/None	Conveyor
			S&R/Orientation	AS/RS

Part type 2				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
3	1	2	(un)Load/Position	Human
			Transportation/None	AGV
	2	1	(un)Load/Position	Human
			Transportation/Position	AGV
			S&R/Position	AS/RS

Part type 3				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
1	1	4	(un)Load/Orientation	Human
			Transportation/None	AGV
	2	2	(un)Load/None	Human
			Transportation/Position	Powered Hand Truck
			S&R/Orientation	AS/RS

Part type 4				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
1	1	5	(un)Load/Orientation	Robot
			Transportation/Orientation	Forklift truck
	2	1	(un)Load/None	Robot
			Handling/Quantity	Human
			Transportation/None	Forklift truck
			S&R/None	AS/RS

Part type 5				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
2	1	4	(un)Load/None	Human
			(re)Handling/Position	Human
			Transportation/Quantity	Conveyor
	2	1	(un)Load/Orientation	Human
			Transportation/None	Conveyor
			S&R/Orientation	AS/RS

Part type 6				
Plan	**Mfg Op**	**M/C**	**Material Handling op.**	**Equipment**
1	1	2	(un)Load/Orientation	Human
			Transportation/None	AGV
	2	5	(un)Load/Position	Human
			Transportation/None	AGV
	3	4	(un)Load/None	Human
			(re)Handling/Position	Human
			Transportation/None	AGV
	4	1	(un)Load/Orientation	Human
			Transportation/Quantity	Conveyor
			S&R/None	AS/RS

Table 31. Solution of the operation allocation model, $X_{sjk}(ip)$ from the sixth iteration

Part, *i*	Process Plan, *p*	Operation, *s*	Machine, *j*	MH Equipment, *e*
1	2	1	2	4
		2	1	4
2	3	1	2	5
		2	1	5
3	1	1	4	5
		2	2	7
4	1	1	5	3
		2	1	3
5	2	1	4	4
		2	1	4
6	1	1	2	5
		2	5	5
		3	4	5
		4	1	4

Table 32: Different costs for the $X_{sjk}(ip)$ assignments from the sixth iteration

Operation cost	4160
M/c Set up cost	590
Transportation cost	4390
Total cost	9140

Table 33. $B_{sjk}(ip)$ Matrix summarized from the P (MH) model, from the sixth iteration.

Part, *i*	Process Plan, *p*	Operation, *s*	Machine, *j*	MH Equipment, *e*
1	2	1	2	4
		2	1	4
2	3	1	2	5
		2	1	5
3	1	1	4	5
		2	2	7
4	1	1	5	3
		2	1	3
5	2	1	4	4
		2	1	4
6	1	1	2	5
		2	5	5
		3	4	5
		4	1	4

Table 34. Solution to the material handling system selection problem $Y_{kij_kc}(ip)$. (Sixth iteration)

Part type 1

Plan	Mfg Op	M/C	Material Handling op.	Equipment
2	1	2	(un)Load/Position	Human
			Transportation/None	Conveyor
	2	1	(un)Load/Orientation	Human
			Transportation/None	Conveyor
			S&R/Orientation	AS/RS

Part type 2

Plan	Mfg Op	M/C	Material Handling op.	Equipment
3	1	2	(un)Load/Position	Human
			Transportation/None	AGV
	2	1	(un)Load/Position	Human
			Transportation/Position	AGV
			S&R/Position	AS/RS

Part type 3

Plan	Mfg Op	M/C	Material Handling op.	Equipment
1	1	4	(un)Load/Orientation	Human
			Transportation/None	AGV
	2	2	(un)Load/None	Human
			Transportation/Position	Powered Hand Truck
			S&R/Orientation	AS/RS

Part type 4

Plan	Mfg Op	M/C	Material Handling op.	Equipment
1	1	5	(un)Load/Orientation	Robot
			Transportation/Orientation	Forklift truck
	2	1	(un)Load/None	Robot
			Handling/Quantity	Human
			Transportation/None	Forklift truck
			S&R/None	AS/RS

Part type 5

Plan	Mfg Op	M/C	Material Handling op.	Equipment
2	1	4	(un)Load/None	Human
			(re)Handling/Position	Human
			Transportation/Quantity	Conveyor
	2	1	(un)Load/Orientation	Human
			Transportation/None	Conveyor
			S&R/Orientation	AS/RS

Part type 6

Plan	Mfg Op	M/C	Material Handling op.	Equipment
1	1	2	(un)Load/Orientation	Human
			Transportation/None	AGV
	2	5	(un)Load/Position	Human
			Transportation/None	AGV
	3	4	(un)Load/None	Human
			(re)Handling/Position	Human
			Transportation/None	AGV
	4	1	(un)Load/Orientation	Human
			Transportation/Quantity	Conveyor
			S&R/None	AS/RS

Table 35. Summary of the objective function values

Model		
Iteration #	**P(OA)**	**P(MH)**
1	6990	134.35
2	8150	126.85
3	8640	131.35
4	8790	124.9
5	9140	127.6
6	9140	127.6

CHAPTER 5. THE OA AND MH SOLVER PROGRAM

The problem was solved using Lingo 5.0 and Microsoft Access 8.0. The process required a great deal of data manipulation; therefore, to reduce the manual work a program was developed to handle the data transfer/manipulation. It also enhanced the capability of the program to be used as an industrial tool. The front end application was developed using Visual Basic 6.0.

The program allows the data manipulation (addition, deleting and editing) through the Microsoft Access program. It generates reports of the final solutions to the problems. The database named OA.MDB contains the data required and is connected through ODBC (Open Database Connectivity) data sources. The models are solved when the program calls a Lingo runtime library that provides access to Lingo's solving capabilities. A Lingo script file was created for each model. This script file is passed by the program to the Lingo runtime library. Finally the output reports are created and can be viewed and printed from within the program.

The program is very simple to understand and can be operated without much technical expertise once the data are entered. The first form that appears when the program is launched is shown in the Figure 1. This form consists of several key components. There is a menu bar and its accompanying menu items. There are two buttons which provide the user the option to solve the problem in two different ways. Each button when clicked launches a new form where the problem can be solved by following the instructions. Finally, there is also an exit button that terminates the application.

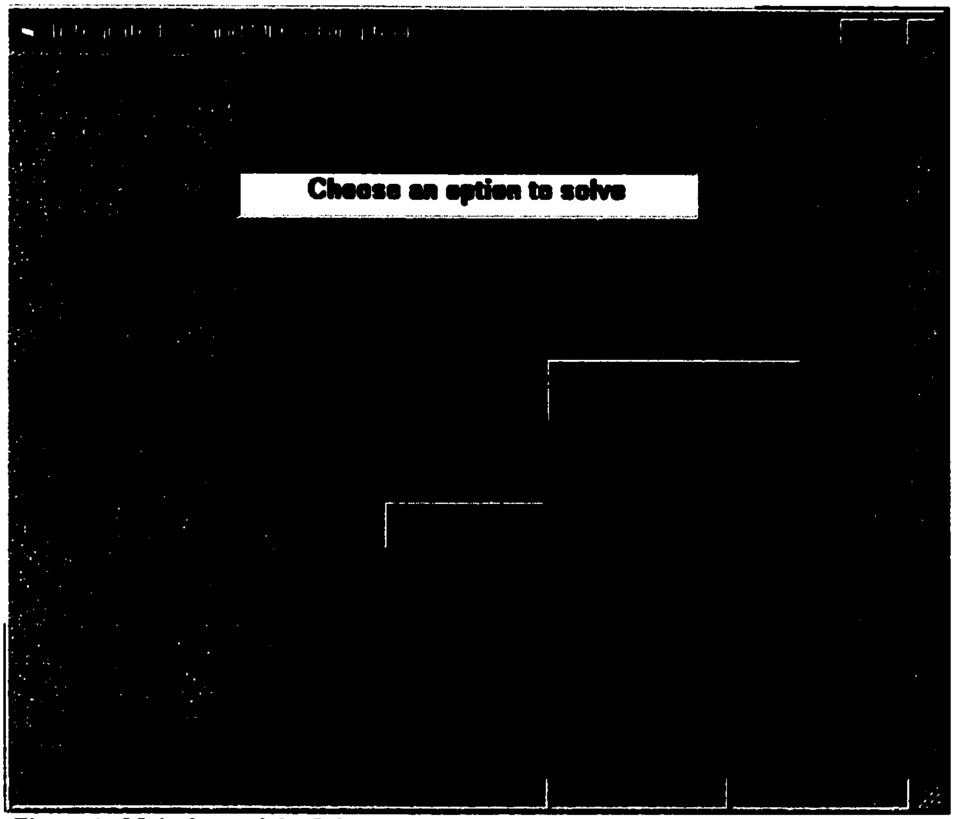


Figure 1. Main form of the Solver program.

The various components in the main window are presented in more detail below.

5.1. The Menu Bar

The menu bar consists of a number of menu entries. The headings in the menu bar drop down to show one or more menu entries. Each menu entry performs a specific function. This is similar to nearly every other application in the Microsoft Windows platform that contains a menu bar. Each heading and the menu entries it contains are described as follows.

The *File* Heading

The ***File*** heading in the menu bar contains two menu entries: ***Open Access*** and ***Exit***. These entries can be seen in Figure 2.

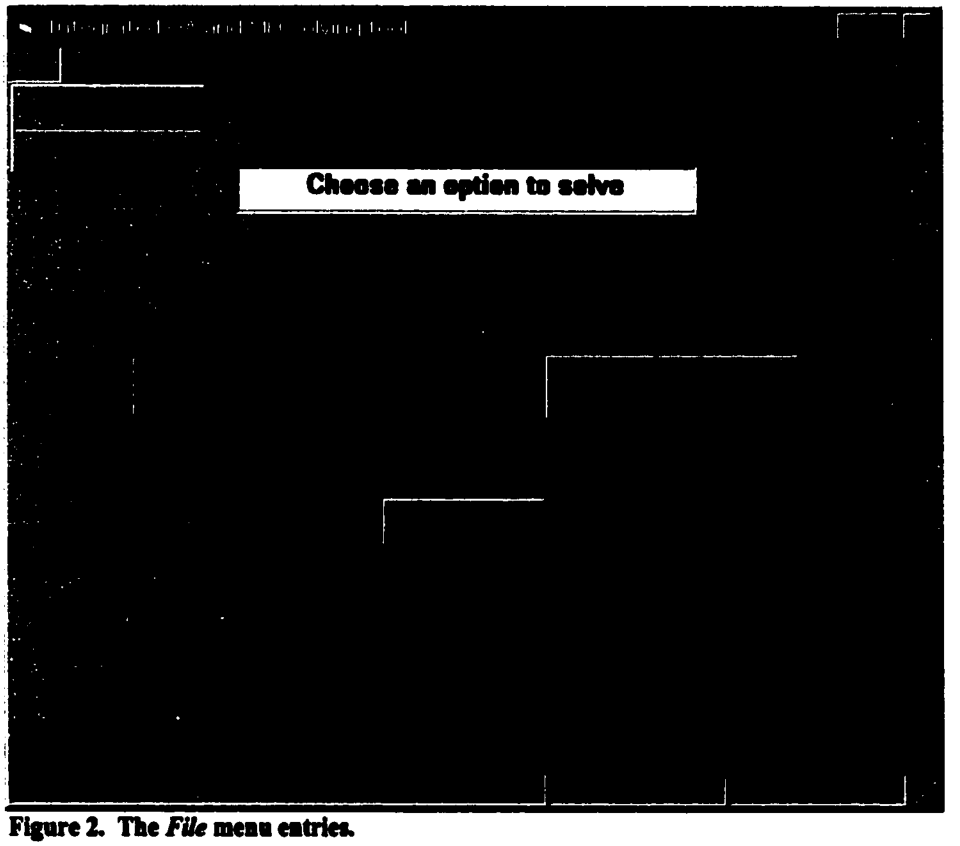


Figure 2. The *File* menu entries.

The ***Open Access*** menu entry will start Microsoft Access with the data file, *OA.MDB*, open for editing. This is the recommended way of editing the data when extensive modifications are required.

The ***Exit*** menu entry simply stops the program. It performs the same function as the *Exit* button at the bottom of the form.

The *Data* Heading

The ***Data*** heading contains a number of menu entries (see Figure 3). When clicked, each menu entry will open a corresponding data table from the database *OA.MDB*. Not all the tables in the database are shown. Some of the tables do not require modifications. These include those listing the major material handling operations and suboperations and the key product variables. In addition, the tables containing the parameter $A_{sj}(ip)$ and $B_{sje}(ip)$ are not shown. The data in these tables is filled in automatically after the Operation Allocation model is solved.

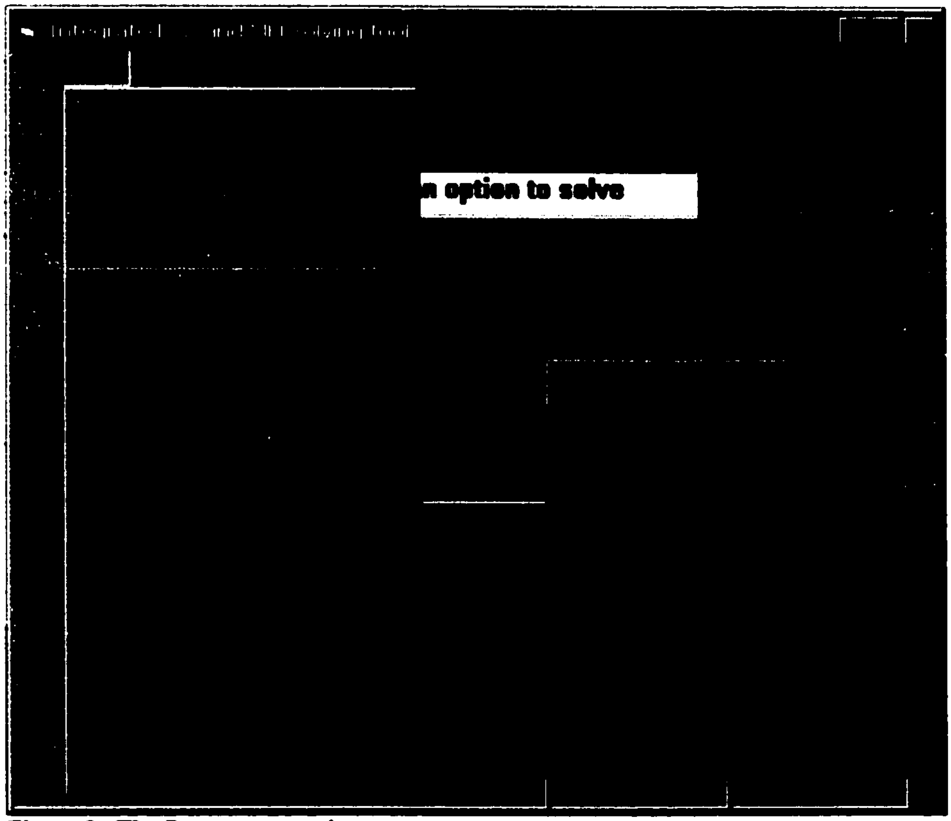


Figure 3. The *Data* menu entries.

The list of all the tables in the database *OA.MDB*, their corresponding menu entries in the menu bar and purpose are summarized in Table 36.

Table 36. *Data* menu entries and associated database tables.

Data Menu Entry	Table in Database	Contents
Parts	Parts	Lists part types and their demands
Plans	Plans	Lists the process plans
MfgOps	MfgOps	Lists the manufacturing operations
Machines	Machines	Lists machines, their capacities (time available) and setup costs
MH_Equip	MH_Equip	Lists the available types of material handling equipment
PartPlan	PartPlan	Lists the possible Part-Plan combinations
PartPlanOp	PartPlanOp	Lists the possible Part-Plan-Manufacturing Operations combinations
PartPlanOpE	PartPlanOpE	Lists the possible Part-Plan-Manufacturing Operations-Material handling equipment combinations
PartPlanOpMCE	PartPlanOpMCE	Lists the Part-Plan-Manufacturing Operations-Machine-Material handling equipment combinations for subsequent per iteration
PartPlanOpMCEMain	PartPlanOpMCEMain	Lists all the possible Part-Plan-Manufacturing Operations-Machine-Material handling equipment combinations
MHC	MHC	Lists the cost of transporting each part type between any two machines using a material handling equipment
MH_Op	MH_Op	Lists the major material handling operations
MH_Subop	MH_Subop	Lists the material handling suboperations
MH_Req	MH_Req	Lists the required material handling operations and suboperations
MH_Req_MH_Equip	MH_Req_MH_Equip	Lists the material handling equipment for the required material handling operations and suboperations for subsequent iterations
MH_Req_MH_EquipMain	MH_Req_MH_Equip Main	Lists the available material handling equipment for the required material handling operations and suboperations
Tech	Tech	Lists the key product variables
W_et	W_et	Lists the ratings for the parameter $\hat{W}_{it}$
W_it	W_it	Lists the ratings for the parameter W_{et}

W_hhe-Time	W_hhe-Time	Lists the ratings for the parameter W_{hhe} and the time required to perform each material handling operation-suboperation combination on each type of material handling equipment

As mentioned above, each menu entry under the ***Data*** heading will open a database table. Figure 4 shows such a data table. In this case, the data table shown was opened by clicking on the menu entry ***Parts***. Various operations can be performed within that table view. It is possible to add, delete or edit a record. Other miscellaneous operations are available through the button bar at the top of the form.

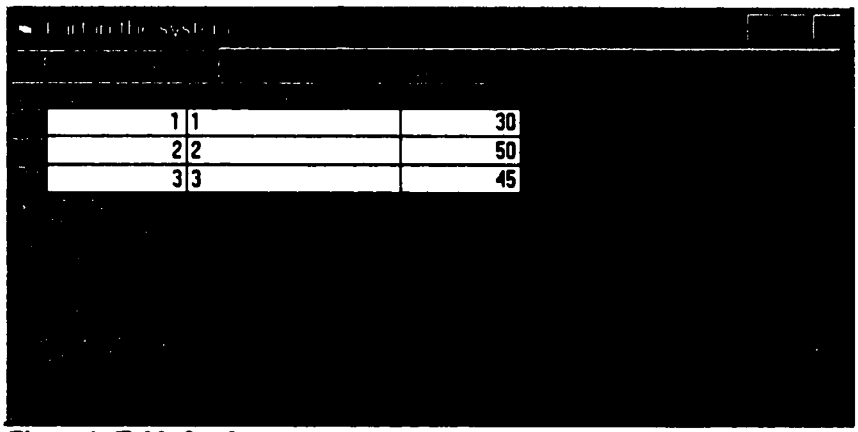


Figure 4. Table for the *parts* menu entry.

To add a new record, the user simply clicks on an empty row and adds the information. To delete a record, the user must highlight the desired row (record) and press the DEL or DELETE key in the keyboard. Other operations are possible and the button bar at the top of the form explicitly lists these.

A complete description of all the tables in the database along with their fields and requirements can be found in the next chapter.

The *Reports* Heading

This heading contains two menu entries as can be seen in Figure 5. The Operation Allocation entry will open an output report for the operation allocation model. Similarly, the Material handling menu entry will open an output report for the material handling system selection model.

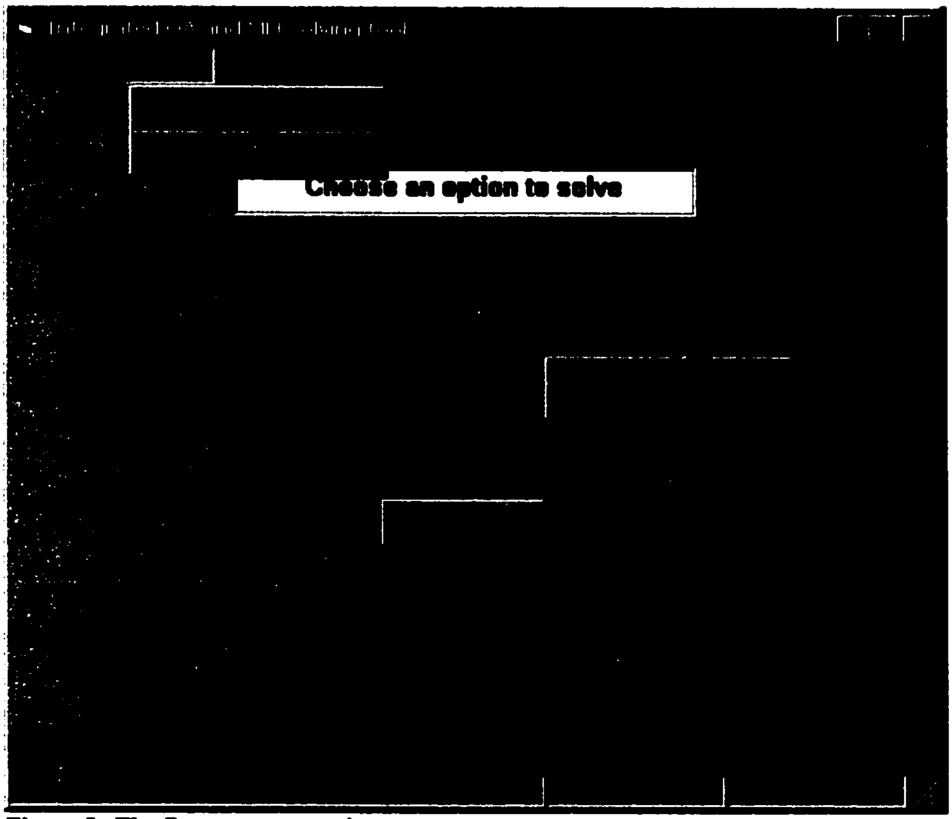
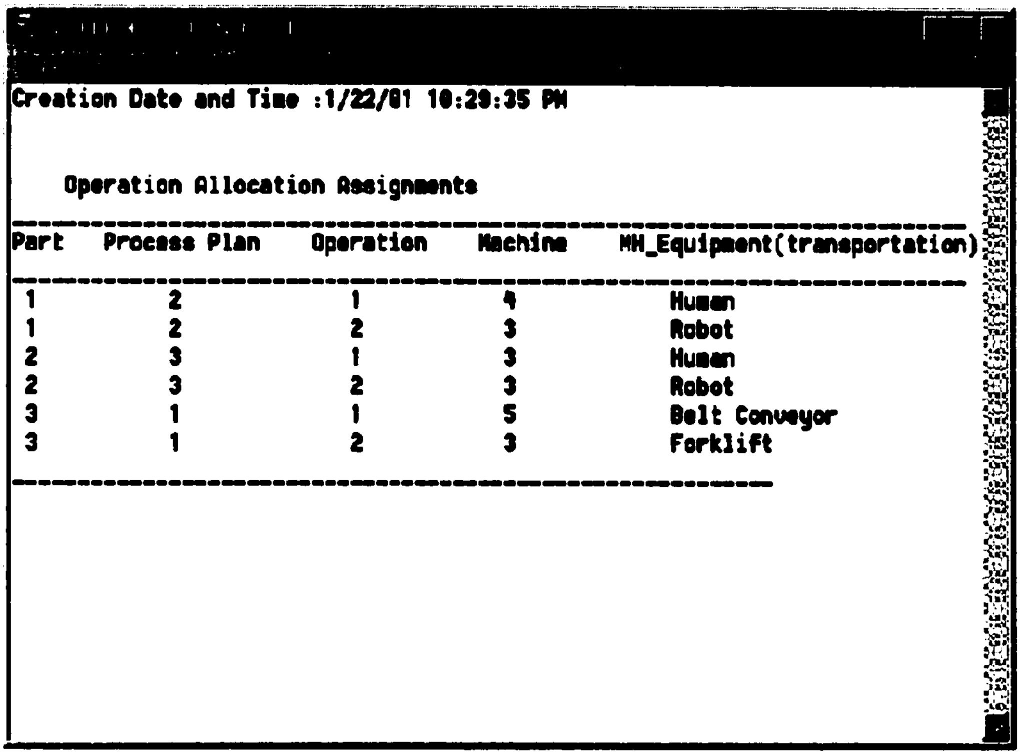


Figure 5. The *Report* menu entries.

The reports are opened with Notepad, which allows for output to be printed. Figure 6 shows a sample report.

Every time the report file is written, its date and time of creation are written in the top line. The output from the model is then listed in an easy to understand format.


Creation Date and Time :1/22/01 10:29:35 PM

Operation Allocation Assignments

Part	Process Plan	Operation	Machine	MH_Equipment(transportation)
1	2	1	4	Human
1	2	2	3	Robot
2	3	1	3	Human
2	3	2	3	Robot
3	1	1	5	Belt Conveyor
3	1	2	3	Forklift

Figure 6. Operation Allocation report window.

The *Help* Heading

The ***Help*** heading contains two menu entries as can be seen in Figure 7. The first menu entry is entitled ***Documentation***. This entry will open a help file in the Microsoft Word format. The file is essentially the same as the current chapter of the thesis report with the addition of the information pertaining to the database *OA.MDB*, its tables and fields. This help document provides a quick and convenient way for the user to become familiar with the program.

The ***About*** menu entry opens a new window with general information about the OA and MH Solver program.

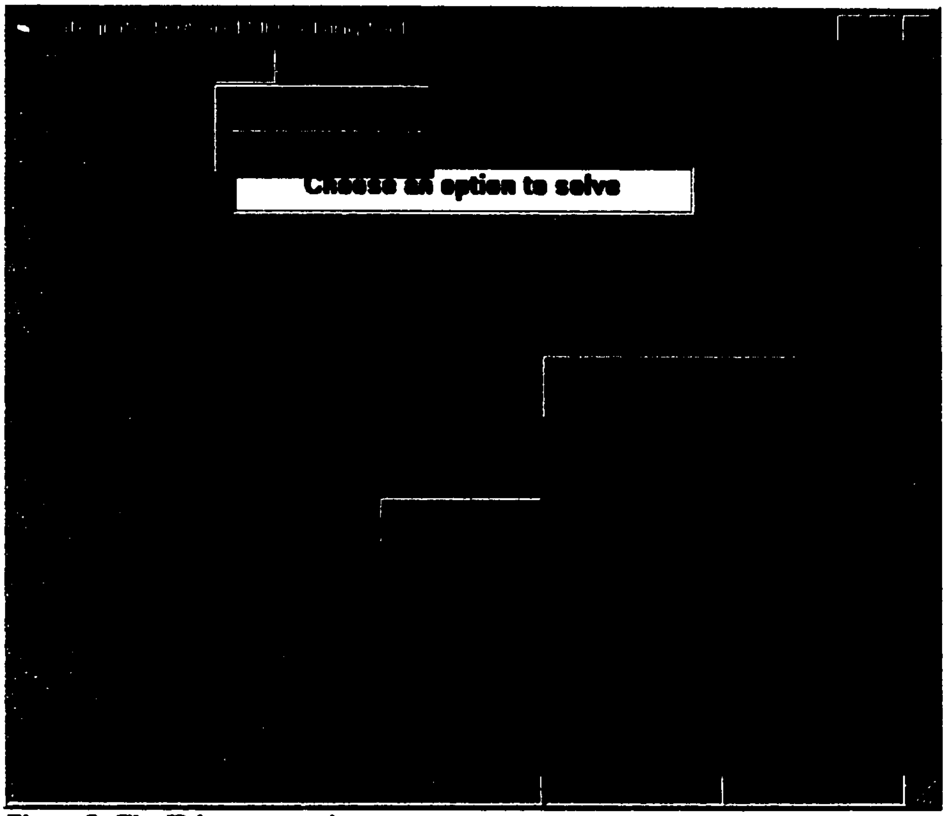


Figure 7. The *Help* menu entries.

5.2. The Sub Forms

The *Solve Step by Step* Form

The form shown in Figure 8 shows the procedure to solve the problem step by step giving user the option of seeing the results of each iteration. It has three boxed buttons to solve the problem. The first two to solve the OA and MH model. The third button prepares the system for the next iteration by running SQL queries and eliminating certain records from the tables MH_Req_MH_Equip and PartPlanOpMCE.

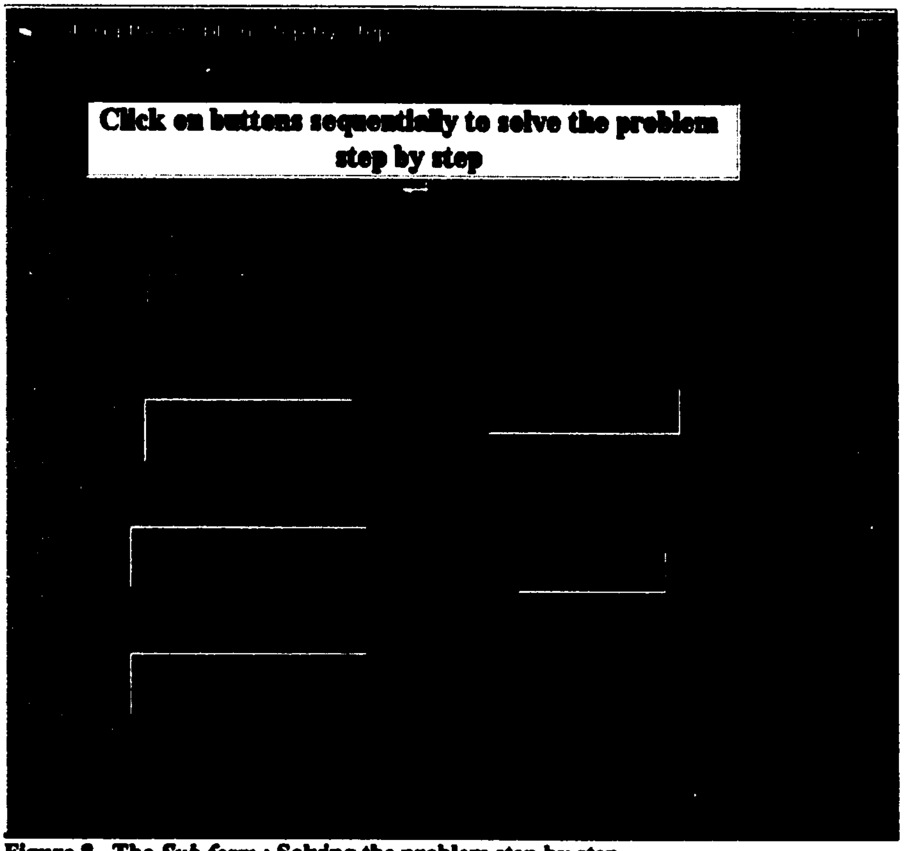


Figure 8. The *Sub form* : Solving the problem step by step.

The two display areas display the result of each model solution. The fourth button exits the form to the main form.

The *Solve Iteratively* Form

The form shown in Figure 9 shows the procedure to solve the problem continuously by using a single button to solve the program until the final solution is found. It has a single boxed button to solve the problem. It includes the solving of the OA and MH model and also preparing the system for the subsequent iterations. The second boxed button exits the form to the main form. There are 3 display areas. The first two display the results for the

OA and MH model and the third display area displays the current iteration being executed.

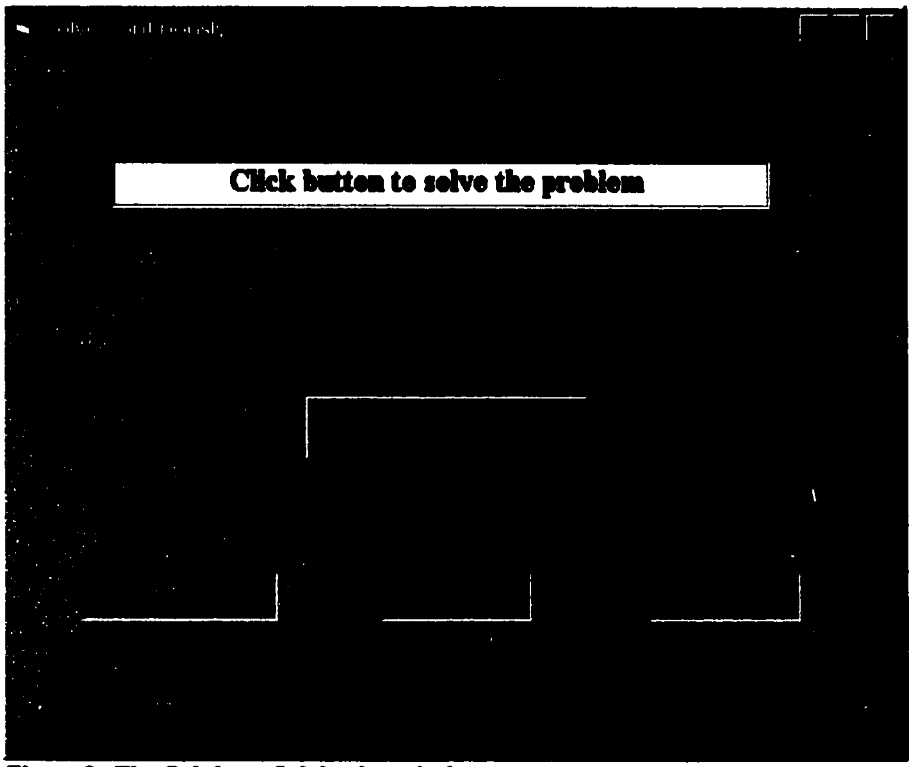


Figure 9. The *Sub form*: Solving iteratively.

5.3. The Buttons

There are four buttons in the 'Solve step by step' window. The boxed buttons are used to solve the two models, while the button at the bottom of the window will exit the program.

The Model solving Buttons

The labels on the buttons clearly indicate their purpose. The top button is labeled ***Solve OA model***. When pressed, the program is instructed to pass on instructions to the Lingo runtime library to solve the operation allocation model. The commands passed to Lingo are presented in a dialog box that is shown immediately after the button is clicked. Figure 8 illustrates this dialog box.

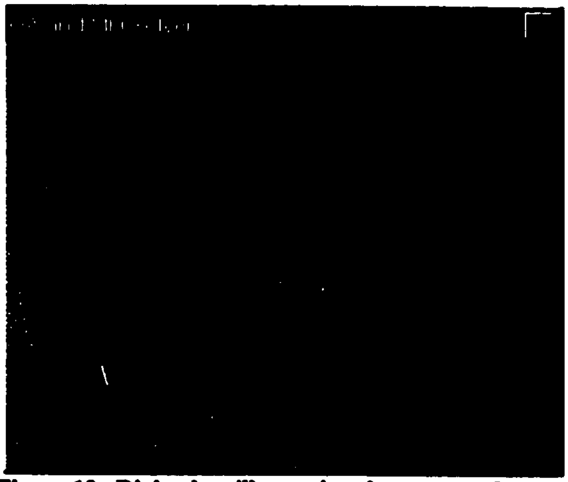


Figure 10. Dialog box illustrating the commands passed to Lingo.

Once Lingo has solved the model and returned command to the program, a dialog box is activated to inform the user about the success of the operation (Figure 11). If Lingo was unable to solve the model, a dialog box warns the user that an error was encountered. If Lingo was successful, a dialog box such as the one in Figure 9 is observed.

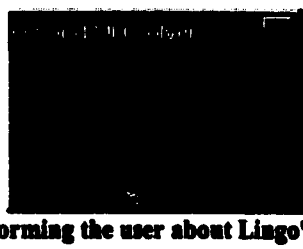


Figure 11. Dialog box informing the user about Lingo's success in solving the model

The main window is then updated to show the value of the objective function. This is shown in the label beside the solve button. Please note that the values of the objective functions are shown to the right of the solver buttons.

The process to solve the material handling system selection problem is similar to that described above for the operation allocation problem. Again, clicking on the button entitled ***Solve MH model*** will start the solution procedure.

The operation allocation problem must be solved prior to solving the material handling system selection problem. This is necessary because the output from the operation allocation model is used as input to the material handling system selection model. As such, the program does not allow the ***Solve MH model*** button to perform its action until the operation allocation model has been solved. Figure 12 shows a dialog box that is displayed to the user if the second button is pressed prior to solving the operation allocation problem.

Figure 12. Dialog box informing the user that the operation allocation problem must be solved before the material handling system selection model can be solved.

Similarly the procedure button ***System Preparation*** can't be performed without solving the first two models. It displays an error box asking to solve the OA and MH models first.

The return to main form button

The third button present in both the sub forms is a simple ***Return to main form*** button. When pressed, this button displays the main form.

The Exit button

The last button is the simple ***Exit*** Button, which when pressed exits the systems.

CHAPTER 6. ANALYSIS AND CONCLUSIONS

An iterative approach was developed and presented here to solve the operation allocation and material handling system selection problems in FMS. The formulation presented is a planning tool to generate some of the design details required to draw a conceptual design of a manufacturing system. The present application of the models is limited to a single cell only, but it may be modified to accommodate multiple cell formulation. The objectives are to select groups of machines, load those machines to manufacture a specific group of parts and also select a suitable as well as economical material handling system to handle those parts at or in between the machines.

The algorithm presented to solve the problem iteratively is described in three steps. Each iteration consists of solving the P (OA) model, followed by the P (MH) model and then eliminating the MH equipment choices for part-process combinations of the P (OA) and P (MH) models. The steps are repeated iteratively until the solutions from the two models stabilize. In the first step, the P (OA) model determines the optimal group of machines to process the part types and then assigns the operations of the part types to the machines. It also chooses a material handling equipment used to transport the part type from one machine to the next. The assignments are made so as to minimize the total costs of operations, machine set-up and material handling (transportation). The assignments are then passed on to the P (MH) model where they are used as input values. Some data manipulation is required to prepare the input values for the second model. The manipulations are done using a Visual Basic application program.

The P (MH) model is solved in the next step. The material handling system selection model then determines the optimal group of material handling equipment to perform all the required material handling operation – sub operations. The equipment is chosen based on its ability to perform the required material handling functions and its ability to handle part types with certain key product characteristics. The model considers several important constraints imposed on the system such as biases towards device combinations and equipment capacity.

The result of the P (MH) model is the selection of the most compatible material handing system to handle a given product- process combination. In the third step, these assignments of material handling equipment for the product-process combination are then passed on to the P (OA) model as a feedback so as to calculate the cost of transportation with the assigned material handling equipment and determining the common solution. In the same step, all choices of MH equipment for the part-process combinations but the one decided by the P (MH) model are eliminated from the P (OA) model. After running the two models for a number of iterations, the solutions to both the models are stabilized and we have a solution common to both the models.

The results of the case study example show that the model can be successfully used as a tool for solving the operation allocation and material handling system selection problems with product design considerations, in an integrated manner. The computational time required to solve the models was quite large on a computer (P-III 50OMhz) as the problem solves for a large number of variables. In the illustrated example in Chapter 4, the model P (OA) solves for more than 30000 variables and over 3000 constraints. The time will increase considerably for larger and more realistic problems, but it is expected to remain computationally feasible. With more powerful machines it is expected to reduce substantially.

Further, to demonstrate the practical application of the work, a front end application program was developed using Visual Basic. The OA - MH Solver is capable of working independently without having to open the LINGO. It hides the intricate details of the integer programming models and allows the users to learn the application very quickly. It allows the data manipulation and viewing reports generated for the solutions by the two models. It also allows the users to choose a way to solve the problem. Two choices are provided. The first is solving step by step in which users can evaluate the intermediate solutions. The other option provides the final solution to the model with the final reports.

The current methodology is a second step towards the integration of the functions of the manufacturing systems. It integrates the operation allocation and material handling functions. Further, it can be used as a stepping stone towards the complete integration of the manufacturing systems by adding more functions to the problem. The current implementation of the model offers flexibility not available in other models. It is possible to solve the operation allocation problems iteratively and hence obtain a solution common to both the models. For instance, solving the problem sequentially will give the most compatible MH equipment but that might not be cost effective. Thus the approach presented here enables a trade-off between the cost and compatibility of MH equipment with a part type.

6.1. Recommendations for Future Work

The current methodology has widened the scope for further research in this area depending on the interests of the researcher. Some of the possibilities are listed below.

First, as discussed earlier, more modules such as machine maintenance or operation scheduling can be included to make the integration process complete. At present, only operation allocation and material handling functions are integrated and are solved iteratively. The methodology allows the two-way communication between the two modules. For more that two modules, it can be either solved iteratively or a single module can be developed to solve the additional modules collectively.

It has been observed that with the increase in the number of variables, there is a considerable increase in the computational time and search space. Another possible extension of the problem can be the application of the non-traditional optimization techniques, e.g., genetic algorithms or neural networks in solving the problem. Genetic algorithms can find solutions to linear and non-linear problems by simultaneously exploring promising areas through mutation, crossover and selection operations. Genetic algorithms have been proved to be an effective and flexible optimization tools that can arrive at optimal or near-optimal solutions to computationally complex problems in reasonable computational time. Most optimization techniques maintain a single solution and improve it until an optimal solution is found, whereas GAs differ in that they maintain and manipulate a family or population of solutions, in the search for an optimal solution. (Michalewicz 1992)

Further, the Visual Basic application program can be extensively overhauled to make it better suited for the industrial application. At present, it provides a general application, which can be customized according to industry requirements and expectation. The OA and MH Solver can become a viable tool for engineers and managers to make decisions faster and in a better way.

With the improvement on the issues and areas discussed above, the OA and MH solver would be enhanced as an application tool in industry.

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APPENDICES

Appendix I.	Lingo Program Files
Appendix II.	Database tables
Appendix III.	OA and MH Solver Program
Appendix IV.	Solver Program Source Code (Back Pocket)

Appendix I. Lingo Program files and user code

Operation Allocation Model

```
MODEL: OA_R.LNG (P (OA))

!-----------------------------------------------------------;
! Lingo program for the Operation Allocation                ;
! Revised to explicitly list sets and generalize            ;
! Author: Ramanpreet Boparai                                ;
! Date: October 2000                                        ;
!-----------------------------------------------------------;

!--------------------- SETS DEFINITION -------------------;
Sets:
     Part:D;
     Plan;
     Mfg_Op;
     MC: M,SC,b;
     MH_Equip:EE;
     PPlan (Part, Plan):Z ;
     PPO (Part, Plan, Mfg_Op);
     PPOE(Part, Plan, Mfg_Op, MH_Equip):Y;
     PPOME(Part, Plan, Mfg_Op, MH_Equip, MC):OC,t;
     Decision (Part, Plan, Mfg_Op, MH_Equip, MC): X;
     MH_Cost (Part, MH_Equip, MC, MC): MHC;
     Lin ( Part, Plan, Mfg_Op, MC, MC, MH_Equip, MH_Equip):
     L;

Endsets

!--------------------- OBJECTIVE FUNCTION ---------------;

!-- Operating Cost ;
C1 = @SUM (PPOME(u,o,v,e,w) :
               D(u)*OC(u,o,v,e,w) * X(u,o,v,e,w));

!-- Setup Cost ;

C2 =  @SUM (MC(w):
               SC(w) * M(w));

!-- Material Handling Cost ;

C3 = @SUM (PPOME(u,o,v,e,w):
@SUM (PPOME(u1,o1,v1,e1,w1)| u #EQ# u1  #AND#  o #EQ# o1
```

```
                  #AND# v1 #EQ# v+1 #AND# w #NE# w1:
          D(u)*MHC(u,e,w,w1) * L(u,o,v,w,w1,e,e1)
         );
     );


!------------------Actual Objective Function-------------;

[OBJ] MIN = C1 + C2 + C3 ;


!------------------ CONSTRAINT SET #1 ------------------;
@FOR (Part(u):
     @SUM (PPlan(u,o):
          Z(u,o)
     ) =1;
);

!------------------ CONSTRAINT SET #2 ------------------;
@FOR (PPO(u,o,v):
     @SUM (PPOE(u,o,v,e):
          Y(u,o,v,e)) = Z(u,o);
  );

!------------------ CONSTRAINT SET #3 ------------------;
@FOR (PPOE(u,o,v,e):
     @SUM (PPOME(u,o,v,e,w):
               X(u,o,v,e,w))
          =Y(u,o,v,e) ;
  );

!------------------ CONSTRAINT SET #4 ------------------;
@FOR (MC(w):
     @SUM (PPOME(u,o,v,e,w):
          X(u,o,v,e,w)
     ) >= M(w);
  );


!------------------ CONSTRAINT SET #5 ------------------;
@FOR (MC(w): [TIME_CONSTRAINT]
     @SUM (PPOME (u,o,v,e,w):
          D(u) * t(u,o,v,e,w) * X(u,o,v,e,w)
     ) <= b(w) * M(w);
  );
```

```
!------------------ CONSTRAINT SET #6 -------------------;
@FOR (PPOME(u,o,v,e,w):
@FOR (PPOME(u1,o1,v1,e1,w1)| u #EQ# u1  #AND#  o #EQ# o1
                         #AND# v1 #EQ# v+1 #AND# w #NE# w1:
          X(u,o,v,e,w) + X(u1,o1,v1,e1,w1)
         -2 * L(u,o,v,w,w1,e,e1) >= 0
     );
  );

!------------------ CONSTRAINT SET #7 --------------------
--- ;
@FOR (PPOME(u,o,v,e,w):
@FOR (PPOME(u1,o1,v1,e1,w1) | u #EQ# u1  #AND#  o #EQ# o1
                         #AND# v1 #EQ# v+1 #AND# w #NE# w1
:
         X(u,o,v,e,w) + X(u1,o1,v1,e1,w1)
         - L(u,o,v,w,w1,e,e1) <= 1
     );
 );




!------------------ INTEGER CONSTRAINTS ------------------
---- ;

! X must be integer ;
@FOR (Part(u):
     @FOR(Plan(o):
          @FOR (Mfg_Op(v):
               @FOR (MH_Equip(e):
                    @FOR (MC(w):
                         @BIN (X(u,o,v,e,w))
                    );
               );
          );
     );
);

! L must be integer ;

@FOR (Part(u):
     @FOR(Plan(o):
          @FOR (Mfg_Op(v):
               @FOR (MC(w):
                    @FOR (MC(w):
                         @FOR (MH_Equip(e):
```

```
                                    @FOR (MH_Equip(e):
                                         @BIN (L(u,o,v,w,w,e,e))
                                    );
                               );
                          );
                     );
                );
           );
);

! Z must be integer ;
@FOR (PPlan(u,o):
     @BIN(Z(u,o))
   );

! M must be integer ;
@For (MC(w):
     @BIN(M(w))
);

@FOR (PPOE(u,o,v,e):
     @BIN(Y(u,o,v,e))
  );


!------ DATA DEFINITION ------ ;
DATA:
     Part = @ODBC('OA', 'PARTS', 'PART');
     D = @ODBC('OA', 'PARTS', 'DEMAND');
     MC = @ODBC('OA', 'MACHINES', 'MACHINE');
     b = @ODBC('OA', 'MACHINES', 'CAPACITY');
     Mfg_Op = @ODBC('OA', 'MFGOPS', 'MFGOP');
     Plan = @ODBC('OA', 'PLANS', 'PLAN');
     MH_Equip = @ODBC('OA', 'MH_EQUIP', 'MH_EQUIP');
     PPlan = @ODBC('OA', 'PARTPLAN','PART','PLAN');
     SC = @ODBC('OA', 'MACHINES', 'SETUP_COST');
     PPO = @ODBC('OA', 'PARTPLANOP', 'PART','PLAN',
     'MFGOP');
     PPOE = @ODBC('OA', 'PARTPLANOPE', 'PART','PLAN',
     'MFGOP', 'EQUIP');
     PPOME = @ODBC('OA', 'PARTPLANOPMCE', 'PART','PLAN',
     'MFGOP','EQUIP', 'MACHINE');
      MHC = @ODBC('OA', 'MHC', 'MHC');
     OC = @ODBC('OA', 'PARTPLANOPMCE', 'MFGOP_COST');
     t = @ODBC('OA', 'PARTPLANOPMCE', 'MFGOP_TIME');
     @POINTER(1) = OBJ;
     @POINTER(2) = @STATUS();
```

ENDDATA

END

Material Handling System Selection Model

```
MODEL: MH_R.LNG (P (MH))

!-------------------------------------------------------------;
! Lingo program for the Sub-Material handling System         ;
! Selection                                                   ;
! Author: Ramanpreet Boparai                                  ;
! Date: October 2000                                          ;
!-------------------------------------------------------------;


!---------------------DEFINE THE SETS--------------------;
SETS:
     Part: Demand;
     Plan;
     Mfg_Op;
     MC:M;
     MH_Equip: Avail, Time ;
     Tech;
     MH_Op;
     MH_Subop;
     A(Part,Plan,Mfg_Op, MC) ;
     Alpha (Part,Plan,Mfg_Op, MC, MH_Op, MH_Subop);
     PME(Part,Plan,Mfg_Op, MC, MH_Op, MH_Subop,MH_Equip);
     Rate_hhe(MH_Equip, MH_Op, MH_Subop): W_ehh, t ;
     Rate_et(MH_Equip, Tech): W_et ;
     Rate_it(Part, Tech): W_it ;
!    HH_Time (MH_Equip, MH_Op, MH_Subop): t;
     Decision (Part,Plan,Mfg_Op, MC, MH_Op,
MH_Subop,MH_Equip):Y ;
ENDSETS


!---------------------OBJECTIVE FUNCTION-----------------;
[OBJ] MAX =
```

```
@SUM( PME(i,p,s,j,h,hbar,e):
     @SUM(A(i,p,s,j):
          W_ehh(e,h,hbar) * Y(i,p,s,j,h,hbar,e) * (1 - @SUM
               (Tech(t): @ABS(W_et(e,t) - W_it(i,t)))/20
             )
          );
      );



!---------------------CONSTRAINT SET #1------------------;

@FOR( Alpha(i,p,s,j,h,hbar):
     @FOR(A(i,p,s,j):
          @SUM( PME(i,p,s,j,h,hbar,e):
               Y(i,p,s,j,h,hbar,e)
          ) = 1;
     );
);


!---------------------CONSTRAINT SET #2------------------;
! Blank for now;



!---------------------CONSTRAINT SET #3------------------;
@FOR( MH_Equip(e):
     @SUM(A(i,p,s,j):
          @SUM( PME(i,p,s,j,h,hbar,e):
               Y(i,p,s,j,h,hbar,e)
          )) >= Avail(e);
     );



!---------------------CONSTRAINT SET #4------------------;
@FOR( MH_Equip(e): [TIME_CONS]
  @SUM( PME(i,p,s,j,h,hbar,e):
     @SUM(A(i,p,s,j):
        Demand(i) * t(e, h,hbar) * Y(i,p,s,j,h,hbar,e)
     )) <= Time(e) * Avail(e);
);


!---------------------Y must be binary------------------;
@FOR( PME(i,p,s,j,h,hbar,e):
```

```
        @BIN( Y(i,p,s,j,h,hbar,e)
        );
);

!-------------------Avail must be binary---------------;

@FOR( MH_Equip(e):
        @BIN( Avail(e)
    );
);

!--------------------DEFINE THE DATA-----------------;
DATA:
    Part = @ODBC('OA', 'PARTS', 'PART');
    Plan = @ODBC('OA', 'PLANS', 'PLAN');
    Demand = @ODBC('OA', 'PARTS', 'DEMAND');
    MH_Equip = @ODBC('OA', 'MH_EQUIP', 'MH_EQUIP');
    MC = @ODBC('OA', 'MACHINES', 'MACHINE');
    Time = @ODBC('OA', 'MH_EQUIP', 'TIME');
    Mfg_Op = @ODBC('OA', 'MFGOPS', 'MFGOP');
    Tech = @ODBC('OA', 'TECH', 'TECH');
    MH_Op = @ODBC('OA', 'MH_OP', 'MH_OP');
    MH_Subop = @ODBC('OA', 'MH_SUBOP', 'MH_SUBOP');
    A = @ODBC('OA', 'A', 'PART','PLAN','MFG_OP',
    'MACHINE');
    Alpha = @ODBC('OA', 'MH_REQ',
    'PART', 'PLAN','MFG_OP', 'MACHINE', 'MH_OP',
    'MH_SUBOP');
    PME = @ODBC('OA','MH_Req_MH_Equip','Part','Plan',
    'Mfg_op', 'Machine','MH_Op','MH_subop','MH_Equip');
    Rate_hhe = @ODBC('OA', 'W_HHE-TIME', 'MH_EQUIP',
    'MHOP', 'MHSUBOP');
    W_ehh = @ODBC('OA', 'W_HHE-TIME', 'W_HHE');
    Rate_et = @ODBC('OA', 'W_ET', 'MH_EQUIP', 'TECH');
    W_et = @ODBC('OA', 'W_ET', 'W_ET');
!   Rate_it = @ODBC('OA', 'W_IT', 'PART', 'TECH');
    W_it = @ODBC('OA', 'W_IT', 'W_IT');
    t = @ODBC('OA', 'W_HHE-TIME', 'MH_TIME');
    @POINTER(1) = OBJ;
    @POINTER(2) = @STATUS();

ENDDATA

END
```

Appendix II. Database Tables

The data required by the operation allocation and material handling models is contained in one Microsoft Access database file – OA.MDB. This table has a number of data tables as described in the table.

Each table in the database is composed of a number of fields. All tables contain an AutoNumber index that is used as the primary key. This field is used to uniquely represent each record in the table. Although the use of this is not required, its presence allows for the construction of queries, forms and reports.

Each data table is described in a tabular format.

Table 37. Description of the tables in the database OA.MDB.

Table Name	Model*	Description
Parts	OA, MH	Lists part types and their demands
Plans	OA, MH	Lists the process plans
MfgOps	OA, MH	Lists the manufacturing operations
Machines	OA, MH	Lists machines, their capacities (time available) and setup costs
MH_Equip	OA, MH	Lists the available types of material handling equipment
PartPlan	OA	Lists the possible Part-Plan combinations
PartPlanOp	OA	Lists the possible Part-Plan-Manufacturing Operations combinations
PartPlanOpE	OA	Lists the possible Part-Plan-Manufacturing Operations-Material handling equipment combinations
PartPlanOpMCE	OA	Lists the Part-Plan-Manufacturing Operations-Machine-Material handling equipment combinations for subsequent per iteration
PartPlanOpMCEMain	OA	Lists all the possible Part-Plan-Manufacturing Operations-Machine-Material handling equipment combinations
MHC	OA	Lists the cost of transporting each part type between any two machines using a material handling equipment
A	OA, MH	Lists the output (solution) from OA problem generated during runtime
MH_Op	MH	Lists the major material handling operations
MH_Subop	MH	Lists the material handling suboperations
MH_Req	MH	Lists the required material handling operations and suboperations
MH_Req_MH_Equip	MH	Lists the material handling equipment for the required material handling operations and suboperations for subsequent iterations
MH_Req_MH_Equip Main	MH	Lists the available material handling equipment for the required material handling operations and suboperations
B	MH	Lists the output (solution) from MH problem generated during runtime only for the transportation material handling operation
Tech	MH	Lists the key product variables
W_et	MH	Lists the ratings for the parameter W_{it}
W_it	MH	Lists the ratings for the parameter W_{et}
W_hhe-Time	MH	Lists the ratings for the parameter W_{hhe} and the time required to perform each material handling operation-suboperation combination on each type of material handling equipment

* Each table is used in at least one of the two models. OA refers to operation allocation and MH refers to material handling model.

Table 38: OA.MDB Database-description of the table: Parts.

Data Table: Parts

Field	Type	Index in model	Description
Part_Index	AutoNumber	--	Record index
Part	Text	i	Part type identifier
Demand	Number	d_i	Demand of part type i

Table 39: OA.MDB Database-description of the table: Plans.

Data Table: Plans

Field	Type	Index in model	Description
Plan_Index	AutoNumber	--	Record index
Plan	Text	p	Process plan type identifier

Table 40: OA.MDB Database-description of the table: MfgOps.

Data Table: MfgOps

Field	Type	Index in model	Description
MfgOp_Index	AutoNumber	--	Record index
MfgOp	Text	s	Manufacturing Operations identifier

Table 41: OA.MDB Database-description of the table: Machine.

Data Table: Machines

Field	Type	Index in model	Description
MC_Index	AutoNumber	--	Record index
Machine	Text	j	Machine identifier
Capacity	Number	b_j	Demand of part type i
Setup_Cost	Currency	SC_j	Setup Cost for machine j

Table 42: OA.MDB Database-description of the tale: MH_Equip.

Data Table: MH_Equip

Field	Type	Index in model	Description
MH_Equip_Index	AutoNumber	--	Record index
MH_Equip	Text	e	Material handling equipment identifier
MH_Equip_d	Text	--	Demand of part type i
Time	Number	T_e	Time available on material handling equipment e

Table 43: OA.MDB Database-description of the table: PartPlan.

Data Table: PartPlan

Field	Type	Index in model	Description
PartPlan_Index	AutoNumber	--	Record index
Part	Text	*I*	Part type identifier
Plan	Text	*P*	Process plan identifier

Table 44: OA.MDB Database-description of the table: PartPlanOp.

Data Table: PartPlanOp

Field	Type	Index in model	Description
PartPlanOp_Index	AutoNumber	--	Record index
Part	Text	*i*	Part type identifier
Plan	Text	*p*	Process plan identifier
MfgOp	Text	*s*	Manufacturing operation identifier

Table 45: OA.MDB Database-description of the table: PartPlanOpE.

Data Table: PartPlanOpE

Field	Type	Index in model	Description
PartPlanOpE_Index	AutoNumber	--	Record index
Part	Text	*i*	Part type identifier
Plan	Text	*p*	Process plan identifier
MfgOp	Text	*s*	Manufacturing operation identifier
Equip	Text	*e*	Material handling equipment identifier

Table 46: OA.MDB Database-description of the table: PartPlanOpMCE.

Data Table: PartPlanOpMCE

Field	Type	Index in model	Description
PartPlanOpMCE_Index	AutoNumber	--	Record index
Part	Text	i	Part type identifier
Plan	Text	p	Process plan identifier
MfgOp	Text	s	Manufacturing operation identifier
Machine	Text	j	Machine identifier
Equip	Text	e	Material handling equipment identifier
MfgOp_Cost	Currency	$OC_{sj}(ip)$	Cost of performing operation s on machine j for the combination (ip)
MfgOp_Time	Number	$t_{sj}(ip)$	Time required to perform operation s on machine j for the combination (ip)

Table 47: OA.MDB Database-description of the table: PartPlanOpMCEMain.

Data Table: PartPlanOpMCEMain

Field	Type	Index in model	Description
PartPlanOpMCE_Index	AutoNumber	--	Record index
Part	Text	i	Part type identifier
Plan	Text	p	Process plan identifier
MfgOp	Text	s	Manufacturing operation identifier
Machine	Text	j	Machine identifier
Equip	Text	e	Material handling equipment identifier
MfgOp_Cost	Currency	$OC_{sj}(ip)$	Cost of performing operation s on machine j for the combination (ip)
MfgOp_Time	Number	$t_{sj}(ip)$	Time required to perform operation s on machine j for the combination (ip)

Table 48: OA.MDB Database-description of the table: MHC.

Data Table: MHC

Field	Type	Index in model	Description
MHC_Index	AutoNumber	--	Record index
Part	Text	i	Part type identifier
MH_Equip	Text	e	Material handling equipment identifier
Machine1	Text	j	Process plan identifier
Machine2	Text	$\hat{j}$	Manufacturing pperation identifier
MHC	Currency	$T_{iej\hat{j}}$	Machine identifier

Table 49: OA.MDB Database-description of the table: A.

Data Table: A

Field	Type	Index in model	Description
A_Index	AutoNumber	--	Record index
Part	Text	i	Part type identifier
Plan	Text	p	Process plan identifier
Mfg_Op	Text	s	Manufacturing operation identifier
Machine	Text	j	Machine identifier

Table 50: OA.MDB Database-description of the table: MH_Op.

Data Table: MH_Op

Field	Type	Index in model	Description
MH_Op_Index	AutoNumber	--	Record index
MH_Op	Text	h	Material handling operation identifier
MH_Op_d	Text	--	Description of material handling operation identifier

Table 51: OA.MDB Database-description of the table: MH_Subop.

Data Table: MH_Subop

Field	Type	Index in model	Description
MH_Subop_Index	AutoNumber	--	Record index
MH_Subop	Text	$\hat{h}$	Material handling suboperation identifier
MH_Subop_d	Text	--	Description of material handling suboperation identifier

Table 52: OA.MDB Database-description of the table: MH_Req.

Data Table: MH_Req

Field	Type	Index in model	Description
MH_Req_Index	AutoNumber	--	Record index
Part	Text	i	Part type identifier
Plan	Text	p	Process plan identifier
Mfg_op	Text	s	Manufacturing operation identifier
Machine	Text	j	Machine identifier
MH_Op	Text	h	Material handling operation identifier
MH_Subop	Text	$\hbar$	Material handling suboperation identifier

Table 53: OA.MDB Database-description of the table: MH_Req_MH_Equip.

Data Table: MH_Req_MH_Equip

Field	Type	Index in model	Description
MH_Req_MH_Equip_Index	AutoNumber	--	Record index
Part	Text	i	Part type identifier
Plan	Text	p	Process plan identifier
Mfg_op	Text	s	Manufacturing operation identifier
Machine	Text	j	Machine identifier
MH_Op	Text	h	Material handling operation identifier
MH_Subop	Text	$\hbar$	Material handling suboperation identifier
MH_Equip	Text	e	Material handling equipment identifier

Table 54: OA.MDB Database-description of the table: MH_Req_MH_EquipMain.

Data Table: MH_Req_MH_EquipMain

Field	Type	Index in model	Description
MH_Req_MH_Equip Main _Index	AutoNumber	--	Record index
Part	Text	*i*	Part type identifier
Plan	Text	*P*	Process plan identifier
Mfg_op	Text	*s*	Manufacturing operation identifier
Machine	Text	*j*	Machine identifier
MH_Op	Text	*h*	Material handling operation identifier
MH_Subop	Text	$\hat{h}$	Material handling suboperation identifier
MH_Equip	Text	*e*	Material handling equipment identifier

Table 55: OA.MDB Database-description of the table: B.

Data Table: B

Field	Type	Index in model	Description
B_Index	AutoNumber	--	Record index
Part	Text	*i*	Part type identifier
Plan	Text	*p*	Process plan identifier
Mfg_opn	Text	*s*	Manufacturing operation identifier
Machine	Text	*j*	Machine identifier
MH_Op	Text	*h*	Material handling operation identifier
MH_Subop	Text	$\hat{h}$	Material handling suboperation identifier
MH_Equip	Text	*e*	Material handling equipment identifier

Table 56: OA.MDB Database-description of the table: Tech.

Data Table: Tech

Field	Type	Index in model	Description
Tech_Index	AutoNumber	--	Record index
Tech	Text	*t*	Key product variable identifier
Tech_d	Text	--	Description of key product variable identifier

Table 57: OA.MDB Database-description of the table: W_it.

Data Table: W_it

Field	Type	Index in model	Description
W_it_Index	AutoNumber	--	Record index
Part	Text	i	Part type identifier
Tech	Text	t	key product variable identifier
W_it	Number	$\hat{W}_{it}$	Relative weight of the product variable t on part type i

Table 58: OA.MDB Database-description of the table: W_et.

Data Table: W_et

Field	Type	Index in model	Description
W_et_Index	AutoNumber	--	Record index
MH_Equip	Text	e	Part type identifier
Tech	Text	t	key product variable identifier
W_et	Number	W_{et}	Relative weight of the product variable t on material handling equipment e

Table 59: OA.MDB Database-description of the table: W_hhe-Time.

Data Table: W_hhe-Time

Field	Type	Index in model	Description
W_hhe_Index	AutoNumber	--	Record index
MH_Equip	Text	e	Material handling equipment identifier
MH_Op	Text	t	Material handling operation identifier
MH_Subop	Text	$\hat{h}$	Material handling suboperation identifier
W_hhe	Number	$\hat{W}_{h\hat{h}e}$	Relative degree of capability of material handling equipment e to perform the operation/sub-operation combination $h\hat{h}$
MH_Time	Number	$t_{h\hat{h}e}$	Time for equipment e to perform material handling operation/sub-operation $h\hat{h}$

Please note that Lingo requires that all set members be type Text, while attributes of those sets should be of type Number (type currency is also acceptable).

Also, Lingo requires that the database be registered as an ODBC Data Source before it can be accessed. The process to register the database is explained in the Lingo 5.0 User Guide (pp. 278-282).

Appendix III. OA and MH Solver Program

The source code for the OA and MH Solver was developed in Visual Basic. Visual Basic saves the form attributes and code in a single file. The module is saved in a different file. For the presented program, there are 27 files, one project file, one module file and 25 form files. All the information about the files is summarized in the table.

The source code for all the files mentioned in the table are given in the CD-ROM attached in the back pocket of this report. The code is sufficiently commented for explanations.

Table 60. Source Code files in the OA and MH Solver program.

File Name	Description
OA and MH Solver.vbp	Project file - A file that keeps track of all programs, forms, menus, libraries, reports, labels, queries, and other types of files that are needed to create an application.
Module1.bas	Module file – A file containing the code to related to the main form of the program
FormAbout.frm	Form file – Information and code for the About dialog box
FormMachine.frm	Form file – Information and code for the form containing the machine data
FormMfgOp.frm	Form file – Information and code for the form containing the manufacturing operations data
FormMH_EquipAvail.frm	Form file – Information and code for the form containing the MH_Req_MH_Equip data
FormMH_EquipAvailMain.frm	Form file – Information and code for the form containing the MH_Req_MH_EquipMain data
FormMH_Op.frm	Form file – Information and code for the form containing the material handling operations data
FormMH_Req.frm	Form file – Information and code for the form containing the material handling requirements data
FormMH_Subop.frm	Form file – Information and code for the form containing the material handling suboperations data
FormMHC.frm	Form file – Information and code for the form containing the transportation costs data
FormMHEquip.frm	Form file – Information and code for the form containing the material handling equipment data
FormPart.frm	Form file – Information and code for the form containing the part types data
FormPlan.frm	Form file – Information and code for the form containing the process plan data
FormPP.frm	Form file – Information and code for the form containing the part-plan data
FormPPO.frm	Form file – Information and code for the form containing the part-plan-manufacturing operation data
FormPPOE.frm	Form file – Information and code for the form containing the part-plan-manufacturing operation-material handling equipment data
FormPPOME.frm	Form file – Information and code for the form containing the part-plan-manufacturing operation-machine-material handling equipment data
FormPPOMEMain.frm	Form file – Information and code for the form containing the part-plan-manufacturing operation-machine-material handling equipment data
FormSolveintegratively.frm	Form file – Information and code for the form which solves the problem in one step

FormSolvestepbystep.frm	**Form file – Information and code for the form which solves the problem in three step**
FormTechP.frm	**Form file – Information and code for the form containing the technology parameter data**
FormW_et.frm	**Form file – Information and code for the form containing the W_{et} data**
FormW_it.frm	**Form file – Information and code for the form containing the $\hat{W}_{it}$ data**
FormW_hhe-time.frm	**Form file – Information and code for the form containing the $\hat{W}_{h\hat{h}e}$ data**
FrmMain.frm	**Form file – Information and code related to the main form of the program**

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