Integration Tools for Material Handling Requirements in Manufacturing Environments

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ABSTRACT

In this paper we focus on integrating material handling requirements with manufacturing operations. The two goals of this paper are: 1) To present a specification framework for both material handling tasks and material handling equipment based on compatibility and economics, and, 2) To present computational tools for evaluating the *system* performance of material handling equipment in the context of a manufacturing plant. We demonstrate these concepts with selected examples.

1. INTRODUCTION

1.1 Motivation

Several factors are changing the use of information technology to integrate operations in a manufacturing enterprise. These include: (a) the global manufacturing enterprise, which often requires quick evaluation of the effect of moving manufacturing operations to other facilities, (b) reuse of existing information pertaining to manufacturing in the context of a new manufacturing facility, and (c) pervasive use of "what-if" analyses to evaluate opportunities for cost reduction in the face of more intense competition in manufacturing. To address the needs imposed by these factors, manufacturing corporations need models that represent their operations. Included is a need for specifications and decision aids for material handling that are well integrated with other information resources pertaining to manufacturing.

2. PREVIOUS WORK

2.1 Process Specification

The goal of the NIST Process Specification Language (PSL) project is to investigate and arrive at a neutral, unifying representation of process information to enable sharing of process data among manufacturing engineering and business applications. This analysis will provide an objective basis from which to develop a comprehensive language and will promote the leveraging of existing work [Knut 1998, Poly 1998].

A related concept is a plan ontology, which is intended to act as a minimum core on which extensions can be made in a consistent, structured fashion. It is meant to support both the meta-level of reasoning about the activities involved in the planning process and the domain object level in which the plans are to be executed. The model sits within the real world in which behavior can occur. Behavior is the performance of one or more real world activities [Tate 1996].

2.2 Rule-based Systems

A number of rule-based systems have been developed for selecting appropriate types of material handling equipment for in-factory moves. Applications include sort conveyors [Luxh 1991], industrial trucks [Malm 1987], and general equipment [Fish 1988, Park 1996, Pete 1998]. The first two situations assume that the system operator has already selected the equipment type, and desires to narrow the specification within that type.

In addition, detailed work has been performed on palletizing systems [Ram 1991, Ram 1992], sort conveyors [Boze 1985, Boze 1988, Shar 1992c, Xie 1996], person-aboard AS/RS [Boze 1990], walk-and-pick systems [Gibs 1992, Shar 1992b], AGV systems [Shar 1990], pick-to-light technology [Shar 1996a, Shar 1996b], and forward pick area specification [Amir 1996, Berg 1998].

A knowledge-based system was devised to assist facility designers in the selection and configuration of materials handling equipment. The system utilizes preference directed search to capture improved designs by dynamically acquiring new preferences throughout the design process [Gabb 1989].

A more involved system consists of an inference engine that branches through a tree guided by collected data essential for solving the material handling equation: Material + Move→ Method. The equation is solved using rules developed to handle relationships between elements and factors of the equation. Plans were for the final system to provide its user with access to vendors specialized in particular handling operations [Hosn 1989, Park 1996].

2.3 Planning Procedures

A construction algorithm for selecting and assigning material handling equipment was developed; the method is computationally attractive and tends to achieve other goals, such as maximizing equipment utilization and minimizing the variations in equipment types as well as the primary goal of cost minimization. The problem is solved using a heuristic that exploits some conceptual similarities to both the knapsack and the loading problem [Hass 1985].

Many companies use materials shipped in bulk and must solve material handling problems associated with these materials. A mathematical programming decision model and methodology are presented that can assist a decision-maker in designing a bulk material handling system and in selecting the specific type of handling or transportation equipment. Model inputs include the following: 1. Capacity of the equipment, 2. Equipment costs, 3. Demand, 4. Budget, and, 5. Equipment compatibility [Velu 1992].

A technique which can be used to design or assist in the design of an integrated materials handling system for a manufacturing facility was developed. The procedure selects the materials handling equipment to be used to perform a given set of moves in order to minimize the system costs associated with the handling, assuming the plant arrangement remains fixed [Webs 1971].

Integration efforts have been focused on a design procedure for a distribution center. Technology selection and operational issues are discussed in terms of input, selection, and evaluation stages along with iterative aspects of top-down decomposition and bottom-up modification [Shar 1991, Shar 1992a]. Included are managerial considerations; transaction data description; replenishment fulfillment; overall structure and detailed subsystem specification in reserve, picking, and sorting areas; and subsystem reconciliation and evaluation [Yoon 1995]. The growing importance of order pick systems (OPSs) has been recognized in both distribution and manufacturing systems. Most studies of conventional warehouse and OPS design imply prescribed sequences of steps in the design process. An important feature of OPSs is the diversity of the material flow, which is transformed by warehouse operations in terms of product and information [Yoon 1996].

Another issue related to the proposed work is that of avoiding too much detail, especially at the early stages. Recent work in a related, but different, domain of facility layout evaluation shows some approaches that may be useful in integrating different types of information. The traditional approaches to facility layout evaluation involved a hundred or more factors in one long list. By eliminating duplicates and focusing on those factors that were based either on the *geometry* of the layout or on other *measurable* elements, it was possible to reduce the long list to 18 criteria, organized into 7 subclasses and 3 main classes [Lin 1999a, Lin 1999b].

3. GENERAL APPROACH

The challenge in this work is to achieve a balance between the rich and diverse data requirements that material handling system designers seek and the practical situation faced by the typical product/process design engineer, while at the same time reflecting the need for rapid prototyping at a level sufficiently detailed to select technologies and obtain budget cost estimates. The method presented relies on *task specifications* of individual and system material handling requirements, and the definition of *topologies* applicable to various material handling technologies. These concepts relate to the goal of developing a *specification framework*. Related to the second goal of developing tools, we show how to derive *decision rules* for screening technologies, and *rapid prototyping* methods to obtain performance and cost estimates. In some sense we are beginning to develop a *knowledge-based approach.* Each of these concepts is explained in more detail below.

3.1 Task Description of Material Handling Requirements

There are two fundamental approaches to describing the tasks to be performed by a material handling system:

a. The *individual task specification*, whether it be a move, storage, inspection, sequencing, or other operation. Here the physical attributes of the load, such as weight, size, fragility, etc., and the task such as vertical displacement, horizontal displacement, positioning accuracy, etc., are important. The main function in this step is to eliminate technologies that are not capable of satisfying the requirements of individual tasks and to match single-task resources with the needs.

b. The *system task requirements* represent another dimension that may lead to a preference for certain technologies. Ultimately, a *resource set* needs to be specified for handling the various system tasks. This approach goes beyond the screening of individual technologies based on requirements of an individual task and relates to system capability, flexibility, and cost.

An idea of an *individual task specification* is given in Table 1. The focus clearly is on the mechanical ability to perform the task. Accordingly, the screening process for technologies uses the *individual resource capabilities*, as shown in Table 2; a more detailed example is given in section 4. This straightforward step has been demonstrated in the past by many. We structure this step in a hierarchical manner, so that major decisions can be made early with only partial information on individual tasks.

In contrast, Table 3 shows some typical *system task requirements*. In this situation it is more difficult to select technologies because of the variety available and the time needed to estimate performance and costs. Here we suggest the development of *decision rules* for identifying promising technologies based on system needs.

This is followed by *rapid prototyping* to obtain performance and cost estimates. The *rapid prototyping* methods are tailored to the various *topologies* for material handling technology. They are at a level appropriate for implementation on a personal computer using nothing more complex than personal productivity software, such as spreadsheets with macros, instead of the more time-consuming analytical procedures such as simulation, stochastic analysis, and optimization. Figure 1 presents the overall procedure that unifies the individual task specifications with the system-level specification of the *resource set* to handle the overall needs.

One of the characteristics of the *resource set* for meeting the needs of *system task requirements* will be the *level of system complexity*. The evaluation of this attribute should be accomplished within a multi-criterion approach.

3.2 Definition of topologies

A fundamental aspect of the overall approach is the classification of material handling technologies into groups that have similar geometric functionality. In a hierarchical system, this is the first level. A preliminary analysis shows that the following classes are needed:

a. Containers, including pallets, slip sheets, wire cages, tote boxes of corrugated and other materials [Tomp 1996a].

b. Accessories, including mechanical grippers, suction grippers, slings and ropes, magnets, pallet forks, clamps, booms.

c. Cranes, including bridge crane, gantry crane, jib crane, mobile crane, single-point hoists, and monorail hosts.

d. Vehicles, including unpowered carts and dollies, platform trucks, forklift trucks, automated guided vehicles (AGV), overhead electrified monorails (OEM). Subclasses are based on

    manual/powered,
    floor supported/overhead supported,
    path-bound/path-free,

horizontal travel only/vertical travel,
position of operator: at floor level, elevated.

e. Conveyors. Subclasses are based on

synchronous/asynchronous,
accumulating/non-accumulating,
spur capability or not,
load supported above/below,
bulk/discrete,
open/enclosed.

f. Sorting devices, including transfer cars, fully populated conveyor loops, conveyor loops with individual carriers or trains of carriers.

g. Storage/retrieval devices, including unit load and bulk load. Subclasses are based on

pallet systems,
items pick systems used in distribution centers.

3.3 Extraction of data

Ideally, the data collection would be part of the manufacturing process specification. Certainly, the elements related to item characteristics and access to the manufacturing process interface should be available to the process designer. If not, then that person should develop the data. Location data for pick-up/deposit points wold depend on the availability of a manufacturing facility layout. If none is available, then a more conservative approach with respect to material handling system design is needed. The format of the data requirements needs to be compatible with that for specifying the manufacturing process, such as IDEF-3, for example.

A major challenge in data extraction is to determine exactly what data is really needed and what is redundant. The approach followed here parallels that developed in a different domain: facility layout evaluation. The traditional approaches to facility layout evaluation involved a hundred or more factors in one long list. *By eliminating duplicates* and focusing on those factors that were based either on the *geometry* of the layout or on other *measurable* elements, it was possible to reduce the long list to 18 criteria, organized into 7 subclasses and 3 main classes [Lin 1999a]. Included were subjective factors such as worker environment, human-related safety, impact on the community, and property-related security.

The data extraction involves the following three steps:

a. Prepare data on individual task specification for early screening of technologies. See example in section 4.

b. Prepare data on individual task specification for narrowing the search to specific models with associated cost and performance parameters. This requires a statement of capability for different material handling equipment. An example of such a capability Table is shown in section 4. After the ineligible technologies have been eliminated by screening, there may remain several options. A filtering procedure is used here, based on the criterion ranking of the user. For individual task specification, the criteria that could be used include:

Closest match of load characteristics to move with equipment load capacity
Best economy of a repetitive move; here a productivity analysis is needed, based on the number of movements and equipment cost data.
Any or all of the criteria in Tables 1 and 2 can be used in a multi-criterion evaluation, with appropriate penalties in the plus/minus directions.

c. Specification of *system task requirements* for selecting technology types that are economical and flexible, and for performing the rapid prototyping. Part of this step focuses on identifying the particular characteristics of *favorite* technologies that result in their repeated selection. For example, in the auto industry the power-and-free overhead conveyor is a *favorite* technology, perhaps due to the combination of item weight, size, and need for buffering and sequencing in the manufacturing process. In clean-room applications the AGV is a popular *favorite*. Another part of this step is a broad-based examination of factors in an effort to identify good candidate technologies based on system task requirements. A more elaborate filtering process is used here, based on the following criteria:

Matching of physical characteristics of the load to equipment load capacity
Flexibility of path selection
Flexibility in reconfiguring system for changed needs
Throughput capability with respect to need
Economy of system

All of these criteria would be used in a multi-criterion evaluation.

3.4 Examples of rapid prototyping methods

In order to evaluate throughput capability and economy of a system, it is suggested that *rapid prototyping* methods be developed and used for each topology, with variations within a topology governed by selection of numerical parameters. Some examples of such methods are given here.

The first two methods represent a series of more detailed procedures that apply to all types of vehicle systems, including forklift, AGV, and OEM.

a. Empty vehicle requirements analysis by factoring, or by first-order approximation followed by factoring [Shar 1997]. The simple factoring method reflects an assumption of first-come, first-served (FCFS) vehicle dispatching, which usually results in pessimistic performance estimates. The first-order approximation method, involving only arithmetic operations in spreadsheet cells, approximates better the typical proximity-based dispatching rules in a vehicle system. See an example in Table 4.

b. Vehicle requirements analysis by representing the vehicle fleet as a single multi-server queue. Once both loaded and empty vehicle trips are known for a design period, then the stochastic behavior of the system can be modeled as a queue. Since the desired fleet utilization is usually below 85%, to avoid downtime of expensive manufacturing process equipment, the modeling shortcut of using a single, multi-server queue, should not result in any gross distortions. Buffers at the manufacturing process interfaces can be represented by a finite queue capacity.

The following method applies to conveyor systems.

c. Although a simulation analysis would be recommended before installing (or configuring) any major conveyor system, it should be possible to select technology and specify configuration with simpler performance models. Specifically, *network flow models* together with *mean-variance analysis* can be used. Since the demand on most conveyor systems in manufacturing is variable throughout the day, some element of reserve capacity is needed. This reserve capacity is usually considerably greater than in vehicle-based systems, with design factors of 0.4 to 0.85 (actual handling capacity compared to theoretical capacity) not being unusual [Boze 1985, Boze 1988]. The design factor can be included in the *decision rules*, since different applications may have different inherent variabilities of demand.

d. For the cranes and hoists it should possible to adapt cycle time formulas from the automated storage/retrieval systems that have been studied so much [Tomp 1996b]. See the related example for AS/RS in Tables 5 and 6.

Many decisions on technology are made before production plans are known completely. The purpose of the rapid prototyping methods is to enable a system planner to make intelligent choices based on uncertain data. Thus, high accuracy is not needed, or if attained, not that meaningful. The rapidly changing business climate suggests that flexibility of technology and ease of implementation may be as or more important as efficiency.

4. MATERIAL HANDLING TASK and EQUIPMENT SPECIFICATIONS

In the context of a manufacturing plant, it would be useful to extract material handling task specifications from existing manufacturing engineering and plant data. This idea is presented via an example. Also, in order to select equipment to accomplish material handling tasks, concise and functional specifications for material handling equipment must be available. We present an example of such a material handling equipment specification for come equipment types.

4.1 Camille Motor Works

The Camille Motor Works (CMW) is a detailed fictitious example of a manufacturing plant [McKa 91]. It manufactures a line of scale model automobiles. There are three main products: GT200, GT250, and GT350. The GT200 is a relatively low cost, die cast model that is sold through large distributors via supermarket magazines and television spot ads. This is a very high volume item and made to stock. CMW constructs the GT200 and other model automobiles using a number of purchased parts and internally fabricated components transformed from raw materials. The products and the floor plan are shown in Figures 2 and 3.

4.2 Route Sheet

The route sheet is a manufacturing engineering information that is essential for defining material handling requirement. The route sheet for GT 200 product in CMW is described below. The GT 200 is composed of a cast body and trim. The cast body is made from 1.5 pounds of melted compound metal that is molded into shape. The trim consists of the stand, decals and plate. The stand is rough and fine machined and the decals are externally purchased. The plate is cut, punched, pressed, and detailed. Once the body and trim are complete, the GT 200 is assembled. The route sheet is shown in Table 7 for the GT 200 model automobile.

4.3 Factory Layout

Another important type of information that is necessary to determine material handling tasks is the spatial arrangements of manufacturing facilities. This information is provided in a 2-D layout, and height information for pick-up and drop-off points. Figure 3 shows the layout for CMW. The height information is used to determine the following task requirement: start and end point height, destination accuracy, and the rack depth. Table 8 shows the height, destination accuracy, rack depth, and the rack locations. The height is the vertical point at which parts are picked-up or dropped off. The destination accuracy is used to determine appropriate equipment capable of such accuracy.

4.4 Parts Information

Data on products and parts that are moved in the plant are also important in defining material handling tasks. Relevant information for GT 200 in CMW is presented in Table 9. The data includes part/product attributes that impact material handling methods.

4.5 Task Specification

Based on the manufacturing engineering data identified above- Route Sheet, Factory Layout, and Parts Information material handling task specifications can be automatically extracted. Figure 4 illustrates this idea. Table 10 show the complete set of material handling tasks required to produce GT 200 in CMW. The information in this Table is extracted from Table 7 (Route Sheet), Figure 3 (Factory Layout) and Table 8 (Height Information), and Table 9 (Parts Information). The list of data items in Table 10 has been selected to help decide on appropriate material handling equipment for the task.

4.6 Material Handling Equipment Resource Specification

It is important to have material handling equipment capabilities stated in a manner that would aid in selecting a specific equipment for a task. Table 11 presents an initial format for such a specification. The information in Table 11 can be used along with the task specification of Table10 to make equipment assignments. One such assignment is indicated in the last column of Table 10.

5. CONCLUSIONS

The task of integrating material handling requirements with manufacturing operations is clearly a difficult one, requiring the development of much detailed data. Undoubtedly, the task will be done, if not by industrial engineers, then by mechanical engineers and computer systems analysts, perhaps aided by vendors. Thus, the question is what is the most appropriate approach. The approach outlined here is designed to take advantage of the information available from technology vendors, system designers, and system operators.

The work described in this paper is in progress. The individual task specification for equipment topology "d. vehicles," was begun in 1999 and will be finished in 2000. The rapid prototyping methods for vehicles and AS/RS were completed in 1999. Additional methods, for conveyor systems and cranes and hoists will be completed in 2000 and 2001, respectively.

Implementation of these methods will be tested in 2000 in one or two manufacturing facilities. The results will undoubtedly lead to some changes and fine-tuning. In addition, as technology changes and as user priorities change, the methods described here will need to be updated.

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Table 1. Example of individual task specification (partial list)

Pick-up point, 3D	Horizontal, vertical access?
Deposit point, 3D	Weight of item
Time for move, min, max	Value of item
Size of item	Orientation requirements
Unit load configuration	Max acceleration on item
Temperature control needs	Balance/stability needs
Vibration control needs	Static or dynamic interface with MH equipment
Static electricity protection	Supports at MH interface
Lifting aids, handles on item	

Table 2. Example of individual resource capability, overhead electrified monorail (partial list)

Pick-up point, min positions from floor, wall, ceiling	Vertical access with hook/hoist
Horizontal access with load carrier	Max travel, 3D
Speed, min, max	Weight capacity
Size capacity	Longit. control: ± 1.5 cm
Axial control: ± 0.5 cm	Max incline: 2 deg.
Floor quality required: none	Orientation: can rotate item
Temperature: ambient	Acceleration
Vibration: frequency	Pendulum swing: amplitude
Balance/stability: good	Static electricity: can protect
Interface with mfg. process equipment: static	Recirculate carriers: yes
Minimum load spacing, m	Asynchronous control: yes
Switching: yes	

Table 3. Example of system task requirements (partial list)

Number of movements per time period
Mean, variance of demand rates
Number of pick-up/deposit points, locations
Capability for change in pick-up/deposit points
Synchronous travel needed?
Sequencing capability needed?
Accumulation capability needed?

Table 4. First-order Approximation Method for Empty Vehicle Travel

Loaded Trips Per Hour		To:						Outbound
		11	12	13	14	15	16	
From:	11	-	13	12	5	2	0	32
	12	4	-	20	11	9	0	44
	13	9	7	-	10	1	0	27
	14	11	6	2	-	0	0	19
	15	0	0	0	0	-	0	0
	16	14	3	7	22	5	0	51
Inbound		38	29	41	48	17	-	173

		Station:	11	12	13	14	15	16	Total
Basic Data:	1.	Inbound, Loaded	38	29	41	48	17	0	173
	2.	Outbound, Loaded	32	44	27	19	0	51	173
Best Case:	3.	Dual Operations	32	29	27	19	0	0	107
	4.	Excess, Empty	6		14	29	17		66
	5.	Deficit, Empty		15				51	66
Worst Case:	6.	Dual Operations	0	0	0	0	0	0	0
	7.	Excess, Empty	38	29	41	48	17	0	173
	8.	Deficit, Empty	32	44	27	19	0	51	173
First-Order Appx.:	9.	Unloading Fraction	38x.2/60 = 0.127	29x.2/60 = 0.097	41x.2/60 = 0.137	48x.2/60 = 0.160	17x.2/60 = 0.057	0	N/A
	10.	Dual Operations	x 32 =4.1	x 44 =.3	x 27 =3.7	x 19 =.0	x 0 =0	x 51 =0	15.1
	11.	Excess, Empty	33.9	24.7	37.3	45.0	17.0	0	157.9
	12.	Deficit, Empty	27.9	39.7	23.3	16.0	0	51.0	157.9

Note: Best case: solve transportation problem with supplies at 1 (6), 3 (14), 4 (29), and 5 (17), and demands at 2 (15) and 6 (51).

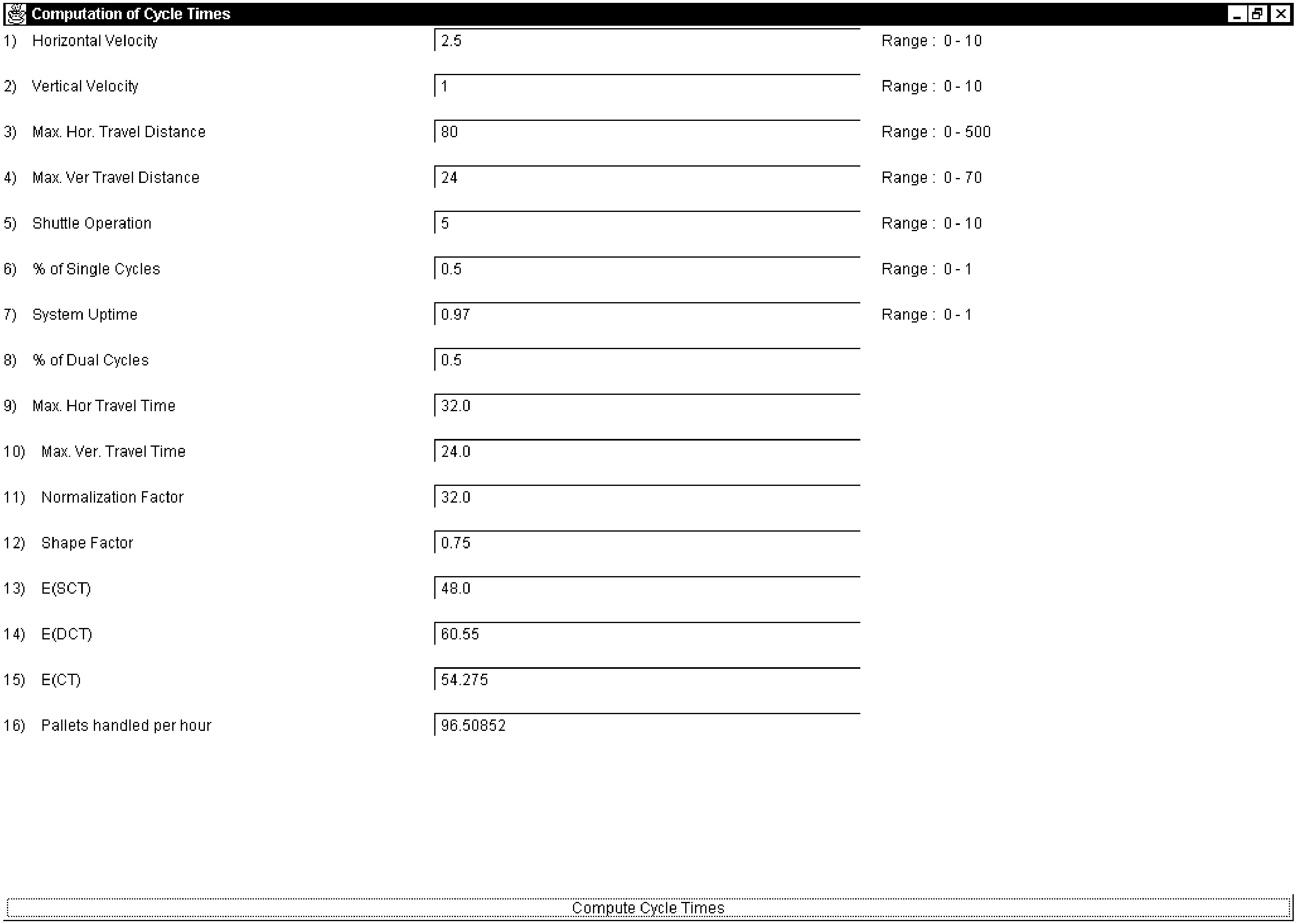
Factoring after worst case:		To:						Outbound
		11	12	13	14	15	16	
From:	11	32x38/173 = 7.0	44x38/173 = 9.7	27x38/173 = 5.9	19x38/173 = 4.2	0x38/173 = 0	51x38/173 = 11.2	31.0
	12	32x29/173 = 5.4	44x29/173 = 7.4	27x29/173 = 4.5	19x29/173 = 3.2	0x29/173 = 0	51x29/173 = 8.5	21.6
	13	32x41/173 = 7.6	44x41/173 = 10.4	27x41/173 = 6.4	19x41/173 = 4.5	0x41/173 = 0	51x41/173 = 12.1	34.6
	14	32x41/173 = 8.9	44x48/173 = 12.2	27x48/173 = 7.5	19x48/173 = 5.3	0x48/173 = 0	51x48/173 = 14.2	42.8
	15	32x17/173 = 3.1	44x17/173 = 4.3	27x17/173 = 2.7	19x17/173 = 1.9	0x17/173 = 0	51x17/173 = 5.0	17.0
	16	32x0/173 = 0	44x0/173 = 0	27x0/173 = 0	19x0/173 = 0	0x0/173 = 0	51x0/173 = 0	0
Inbound		25	36.6	20.6	13.8	0	51	147

Notes: 1) Factoring after <u>worst case</u>: [Sum of dual operations = 26.1]
2) Outbound and Inbound Totals ignore diagonal elements.

Factoring after 1st Order Appx.		To:						Outbound
		11	12	13	14	15	16	
From:	11	27.9x33.9 / 157.9 = 6.0	39.7x33.9 / 157.9 = 8.5	23.3x33.9 / 157.9 = 5.0	16x33.9 / 157.9 = 3.4	0x33.9 / 157.9 = 0	51x33.9 / 157.9 = 10.9	27.8
	12	27.9x24.7 / 157.9 = 4.4	39.7x24.7 / 157.9 = 6.2	23.3x24.7 / 157.9 = 3.6	16x24.7 / 157.9 = 2.5	0x24.7 / 157.9 = 0	51x24.7 / 157.9 = 8.0	18.5
	13	27.9x37.3 / 157.9 = 6.6	39.7x37.3 / 157.9 = 9.4	23.3x37.3 / 157.9 = 5.5	16x37.3 / 157.9 = 3.8	0x37.3 / 157.9 = 0	51x37.3 / 157.9 =12.0	31.8
	14	27.9x45.0 / 157.9 = 8.0	39.7x45.0 / 157.9= 11.3	23.3x45.0 / 157.9 = 6.6	16x45.0 / 157.9 = 4.6	0x45.0 / 157.9 = 0	51x45.0 / 157.9 = 14.5	40.4
	15	27.9x17.0 / 157.9 = 3.0	39.7x17.0 / 157.9 = 4.3	23.3x17.0 / 157.9 = 2.5	16x17.0 / 157.9 = 1.7	0x17.0 / 157.9 = 0	51x17.0 / 157.9 = 5.5	17.0
	16	27.9x0 / 157.9 = 0	39.7x0 / 157.9 = 0	23.3x0 / 157.9 = 0	16x0 / 157.9 = 0	0x0 / 157.9 = 0	51x0 / 157.9 = 0	0
Inbound		22	33.5	17.7	11.4	0	50.9	135.5

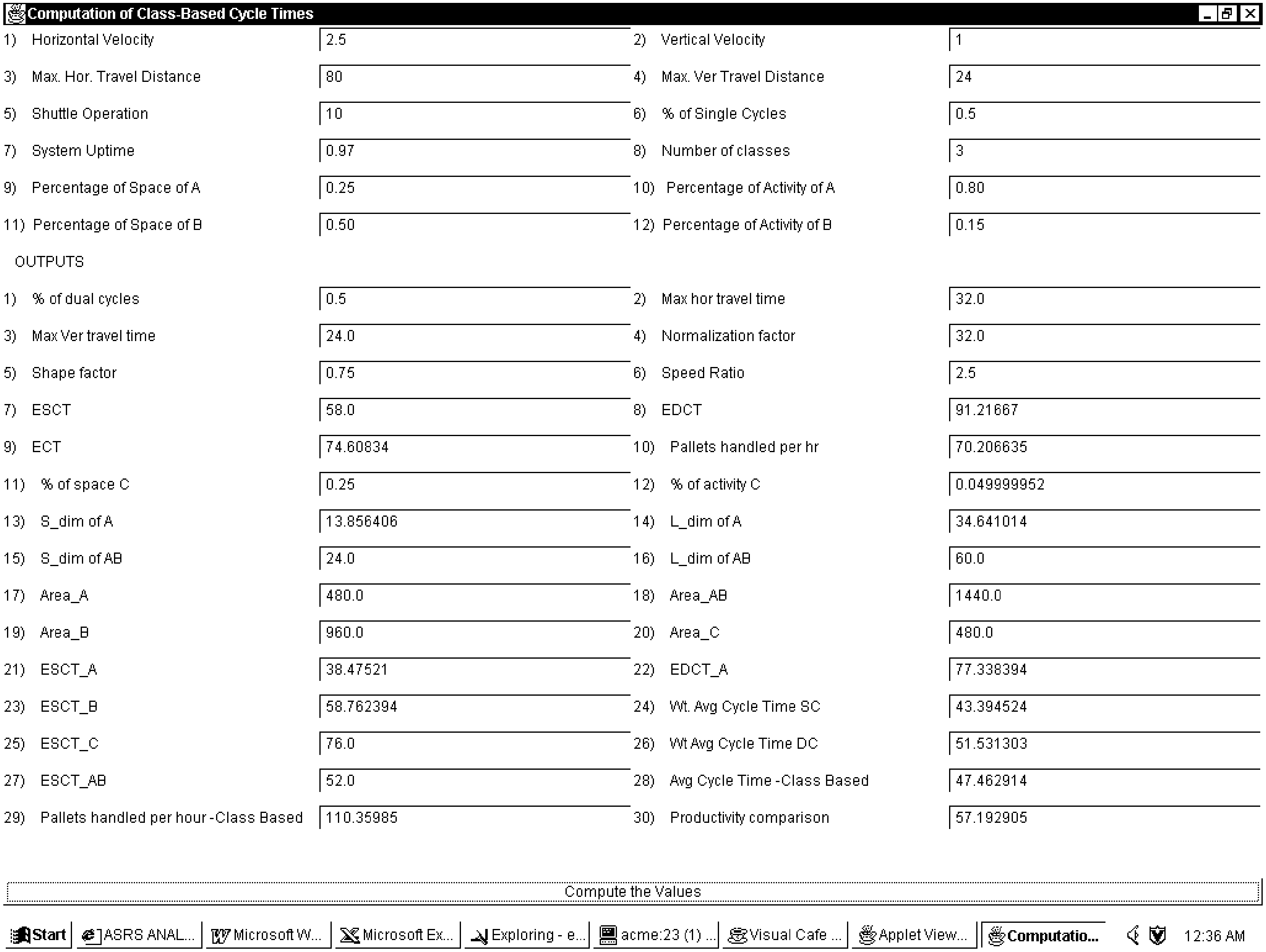
<u>Notes</u>: 1) Factoring after <u>first-order approximation</u>: [Sum of additional dual operations = 26.1 ==> 37.4 Total]
2) Outbound and Inbound Totals ignore diagonal elements.

Table 5. Screen display for AS/RS rapid prototyping, part 1



1) Horizontal Velocity	2.5	Range : 0 - 10
2) Vertical Velocity	1	Range : 0 - 10
3) Max. Hor. Travel Distance	80	Range : 0 - 500
4) Max. Ver Travel Distance	24	Range : 0 - 70
5) Shuttle Operation	5	Range : 0 - 10
6) % of Single Cycles	0.5	Range : 0 - 1
7) System Uptime	0.97	Range : 0 - 1
8) % of Dual Cycles	0.5	
9) Max. Hor Travel Time	32.0	
10) Max. Ver. Travel Time	24.0	
11) Normalization Factor	32.0	
12) Shape Factor	0.75	
13) E(SCT)	48.0	
14) E(DCT)	60.55	
15) E(CT)	54.275	
16) Pallets handled per hour	96.50852	

Table 6. Screen display for AS/RS rapid prototyping, part 2



1) Horizontal Velocity	2.5	2) Vertical Velocity	1
3) Max. Hor. Travel Distance	80	4) Max. Ver Travel Distance	24
5) Shuttle Operation	10	6) % of Single Cycles	0.5
7) System Uptime	0.97	8) Number of classes	3
9) Percentage of Space of A	0.25	10) Percentage of Activity of A	0.80
11) Percentage of Space of B	0.50	12) Percentage of Activity of B	0.15

OUTPUTS

1) % of dual cycles	0.5	2) Max hor travel time	32.0
3) Max Ver travel time	24.0	4) Normalization factor	32.0
5) Shape factor	0.75	6) Speed Ratio	2.5
7) ESCT	58.0	8) EDCT	91.21667
9) ECT	74.60834	10) Pallets handled per hr	70.206635
11) % of space C	0.25	12) % of activity C	0.049999952
13) S_dim of A	13.856406	14) L_dim of A	34.641014
15) S_dim of AB	24.0	16) L_dim of AB	60.0
17) Area_A	480.0	18) Area_AB	1440.0
19) Area_B	960.0	20) Area_C	480.0
21) ESCT_A	38.47521	22) EDCT_A	77.338394
23) ESCT_B	58.762394	24) Wt. Avg Cycle Time SC	43.394524
25) ESCT_C	76.0	26) Wt Avg Cycle Time DC	51.531303
27) ESCT_AB	52.0	28) Avg Cycle Time -Class Based	47.462914
29) Pallets handled per hour -Class Based	110.35985	30) Productivity comparison	57.192905

Table 7. Route Sheet for GT 200 in CMW

Product Name	**GT 200**	
Quantity	**250**	
	Routing Station	
Parts	**From**	**To**
Wood Component	Purch Store	Msload
Wood Component	Msload	M001
Wood Component	M001	M002
Wood Component	M002	M003
Wood Component	M003	M004
Wood Component	M004	M005
Wood Component	M005	Msunload
2XX Stand	Msunload	2xx Store
Cast Metal Compound	Raw Store	F001
Cast Metal Compound	F001	F004
Cast Metal Compound	F004	Rack Bank
200 Body	Rack Bank	Assybench3
Sheet Metal	Raw Store	S001
2xx Plate 01	S001	S002
2xx Plate 02	S002	S003
2xx Plate 03	S003	2xx Store
2xx Plate 03	2xx Store	Smbench
200 Plate	Smbench	Assybench3
2XX Stand	2xx Store	Assybench3
200 Decal	Purch Store	Assybench3
GT 200	Assybench3	Final Store

Table 8. Height Information for plant in CMW

Stations	Height (in)	Destination Accuracy (in)	Rack Depth (# of UL)	Rack Locations
Raw Store	6	0.5	2	L001-L020
Raw Store	66	0.5	2	L021-L040
Purch Store	6	0.5	1	L001-L004
Purch Store	66	0.5	1	L005-L008
2xx Store	6	0.5	2	L001-L015
2xx Store	66	0.5	2	L016-L030
Final Store	6	0.5	1	L001-L004
Final Store	66	0.5	1	L005-L008
Msload	36	0.25	-	-
Msunload	36	0.25	-	-
M001	24	2	-	-
M002	24	2	-	-
M003	24	2	-	-
M004	24	2	-	-
M005	24	2	-	-
F001	36	2	-	-
F004	36	2	-	-
Rack Bank	48	2	-	-
S001	36	2	-	-
S002	36	2	-	-
S003	36	2	-	-
Smbench	24	2	-	-
Assybench3	24	2	-	-

Table 9. Parts Information for GT 200 in CMW

Parts	Weight (lbs)	Unit Load Height (in)	Unit Load Size (LxW) (in)		Unit Load Packing	Unit Load Bottom Surface	Nature	Temperature ^{o}F
Wood Compound	3	36	48	36	loose	flat-rough	sturdy	70
Wood Compound	2.9	36	48	36	loose	flat-rough	sturdy	70
Wood Compound	2.85	36	48	36	loose	flat-rough	sturdy	70
Wood Compound	2.8	36	48	36	loose	flat-rough	sturdy	70
Wood Compound	2.7	36	48	36	loose	flat-rough	sturdy	70
Wood Compound	2.65	36	48	36	loose	flat-rough	sturdy	70
Wood Compound	2.6	36	48	36	loose	flat-rough	sturdy	70
2XX Stand	2.5	36	48	36	average	flat-smooth	fragile	70
Cast Metal Compound	2	60	48	40	loose	flat-smooth	sturdy	70
Cast Metal Compound	2	60	48	40	loose	flat-smooth	sturdy	70
Cast Metal Compound	1.5	60	48	40	loose	flat-smooth	sturdy	70
200 Body	1.5	36	48	40	average	flat-rough	fragile	70
Sheet Metal	3	24	36	24	loose	flat-smooth	sturdy	70
2xx Plate 01	2.8	24	36	24	loose	flat-smooth	sturdy	70
2xx Plate 02	2.6	24	36	24	loose	flat-rough	sturdy	70
2xx Plate 03	2.4	24	36	24	loose	flat-rough	sturdy	70
2xx Plate 03	2.4	24	36	24	loose	flat-rough	sturdy	70
200 Plate	2.5	24	48	40	average	flat-rough	fragile	70
2XX Stand	2.5	48	48	40	average	flat-smooth	fragile	70
200 Decal	2	48	48	40	average	flat-smooth	fragile	70
GT 200	8.5	48	48	40	tight	flat-smooth	fragile	70

Table 10. Task Specifications for GT 200 in CMW

Material Handling Task Specification																					
				Move								Material							Item		
Task #	Product GT200			Start Point		End Point		Start point Height (in)	End Point Height (in)	Destination Accuracy (in)	Rack Depth (# of UL)	Quantity (UL)	Weight (lbs) (UL)	Height (in) (UL)	Size (LxW) (in) (UL)		Packing (UL)	Bottom Surface (UL)	Nature	Temperature ^{o}F	Equipment Number
1	Wood Component	Purch Store	Msload	71	27	38	109	6	36	0.25	-	250	750	36	48	36	loose	flat-rough	sturdy	70	22
2	Wood Component	Msload	M001	38	109	22	114	36	24	2	-	250	725	36	48	36	loose	flat-rough	sturdy	70	15
3	Wood Component	M001	M002	22	114	22	106	24	24	2	-	250	713	36	48	36	loose	flat-rough	sturdy	70	15
4	Wood Component	M002	M003	22	106	22	98	24	24	2	-	250	700	36	48	36	loose	flat-rough	sturdy	70	15
5	Wood Component	M003	M004	22	98	22	90	24	24	2	-	250	675	36	48	36	loose	flat-rough	sturdy	70	15
6	Wood Component	M004	M005	22	90	22	82	24	24	2	-	250	663	36	48	36	loose	flat-rough	sturdy	70	15
7	Wood Component	M005	Msunload	22	82	38	87	24	24	0.25	-	250	650	36	48	36	loose	flat-rough	sturdy	70	15
8	2XX Stand	Msunload	2xx Store	38	87	71	111	36	66	0.5	2	250	625	36	48	36	average	flat-smooth	fragile	70	22
9	Cast Metal Compound	Raw Store	F001	71	154	18	168	6	36	2	-	250	500	60	48	40	loose	flat-smooth	sturdy	70	22
10	Cast Metal Compound	F001	F004	18	168	33	154	36	36	2	-	250	500	60	48	40	loose	flat-smooth	sturdy	70	15
11	Cast Metal Compound	F004	Rack Bank	33	154	48	162	36	48	2	-	250	375	60	48	40	loose	flat-smooth	sturdy	70	15
12	200 Body	Rack Bank	Assybench3	48	162	35	12	48	24	2	-	250	375	36	48	40	average	flat-rough	fragile	70	15
13	Sheet Metal	Raw Store	S001	71	154	97	160	66	36	2	-	250	750	24	36	24	loose	flat-smooth	sturdy	70	22
14	2xx Plate 01	S001	S002	97	160	97	140	36	36	2	-	250	700	24	36	24	loose	flat-smooth	sturdy	70	15
15	2xx Plate 02	S002	S003	97	140	97	120	36	36	2	-	250	650	24	36	24	loose	flat-rough	sturdy	70	15
16	2xx Plate 03	S003	2xx Store	97	120	71	111	36	66	0.5	2	250	600	24	36	24	loose	flat-rough	sturdy	70	22
17	2xx Plate 03	2xx Store	Smbench	71	111	90	95	66	24	2	-	250	600	24	36	24	loose	flat-rough	sturdy	70	22
18	200 Plate	Smbench	Assybench3	90	95	35	12	24	24	2	-	250	625	24	48	40	average	flat-rough	fragile	70	22
19	2XX Stand	2xx Store	Assybench3	71	111	35	0	66	24	2	-	250	625	48	48	40	average	flat-smooth	fragile	70	22
20	200 Decal	Purch Store	Assybench3	71	27	35	12	66	24	2	-	250	500	48	48	40	average	flat-smooth	fragile	70	22
21	GT 200	Assybench3	Final Store	35	12	71	14	24	6	0.5	1	250	2125	48	48	40	tight	flat-smooth	fragile	70	22

Table 11.An example of Material Handling Equipment Specification

Equipment Number	Material Handling Resource	Capacity (lbs)	Width (in)	Horizontal Movement	Vertical Movement	Lifting Height (in)	Travel Speed (ft/min)	Turing Radius (in)	Aisle Width Needed (in)	Forks Size (T/W/L)			Platform Size (LxW) (in)	
1	2-Wheel Hand Truck	300	-	yes	no	-	-	-	15	-	-	-	-	-
2	2-Wheel Hand Truck	500	-	yes	no	-	-	-	15	-	-	-	-	-
3	2-Wheel Hand Truck	600	-	yes	no	-	-	-	15	-	-	-	-	-
4	4-Wheel Hand Truck	300	-	yes	no	-	-	-	15	-	-	-	-	-
5	4-Wheel Hand Truck	500	-	yes	no	-	-	-	15	-	-	-	-	-
6	4-Wheel Hand Truck	600	-	yes	no	-	-	-	15	-	-	-	-	-
7	Manual Platform Truck	500	-	yes	no	-	-	-	24	-	-	-	36	24
8	Manual Platform Truck	1000	-	yes	no	-	-	-	24	-	-	-	36	24
9	Manual Platform Truck	1000	-	yes	no	-	-	-	24	-	-	-	48	24
10	Manual Platform Truck	1000	-	yes	no	-	-	-	24	-	-	-	48	24
11	Manual Platform Truck	2000	-	yes	no	-	-	-	24	-	-	-	48	24
12	Manual Platform Truck	500	-	yes	no	-	-	-	30	-	-	-	60	30
13	Manual Platform Truck	1000	-	yes	no	-	-	-	30	-	-	-	60	30
14	Manual Platform Truck	2000	-	yes	no	-	-	-	30	-	-	-	60	30
15	Manual Pallet Jack	5000	-	yes	no	6	-	-	21	1.5	6	36	-	-
16	Manual Pallet Jack	5000	-	yes	no	6	-	-	21	1.5	6	42	-	-
17	Manual Pallet Jack	5000	-	yes	no	6	-	-	27	1.5	6	42	-	-
18	Manual Pallet Jack	5000	-	yes	no	6	-	-	27	1.5	6	48	-	-
19	Manual Pallet Jack	6000	-	yes	no	7	-	-	20	1.5	6	36	-	-
20	Manual Pallet Jack	6000	-	yes	no	7	-	-	20	1.5	6	42	-	-
21	Manual Pallet Jack	6000	-	yes	no	7	-	-	27	1.5	6	42	-	-
22	Manual Pallet Jack	6000	-	yes	no	7	-	-	27	1.5	6	48	-	-
23	Sit-Down Counterbalanced Truck	3000	-	yes	yes	127	12	77	91	1.5	4	36	-	-
24	Sit-Down Counterbalanced Truck	5000	-	yes	yes	123	9	78	92	1.8	4	42	-	-
25	Sit-Down Counterbalanced Truck	3000	-	yes	yes	122	7	72	85	1.5	4	36	-	-
26	Sit-Down Counterbalanced Truck	8000	-	yes	yes	120	6	84	100	2	5	42	-	-
27	Stand-Up Counterbalanced Truck	4000	-	yes	yes	95	7	66	91	1.8	3.9	42	-	-
28	Stand-Up Counterbalanced Truck	4500	-	yes	yes	242	6	73	107	1.8	3.9	42	-	-
29	Stand-Up Counterbalanced Truck	4000	-	yes	yes	452	6	92	183	1.8	4	42	-	-
30	Stand-Up Counterbalanced Truck	3000	-	yes	yes	119	6	69	100	1.8	4	42	-	-
31	Skate Wheel Conveyor	550	12	yes	no	-	-	-	-	-	-	-	-	-
32	Skate Wheel Conveyor	550	18	yes	no	-	-	-	-	-	-	-	-	-
33	Skate Wheel Conveyor	550	24	yes	no	-	-	-	-	-	-	-	-	-
34	Gravity Roller Conveyor	1000	16	yes	no	-	-	-	-	-	-	-	-	-
35	Gravity Roller Conveyor	1000	18	yes	no	-	-	-	-	-	-	-	-	-

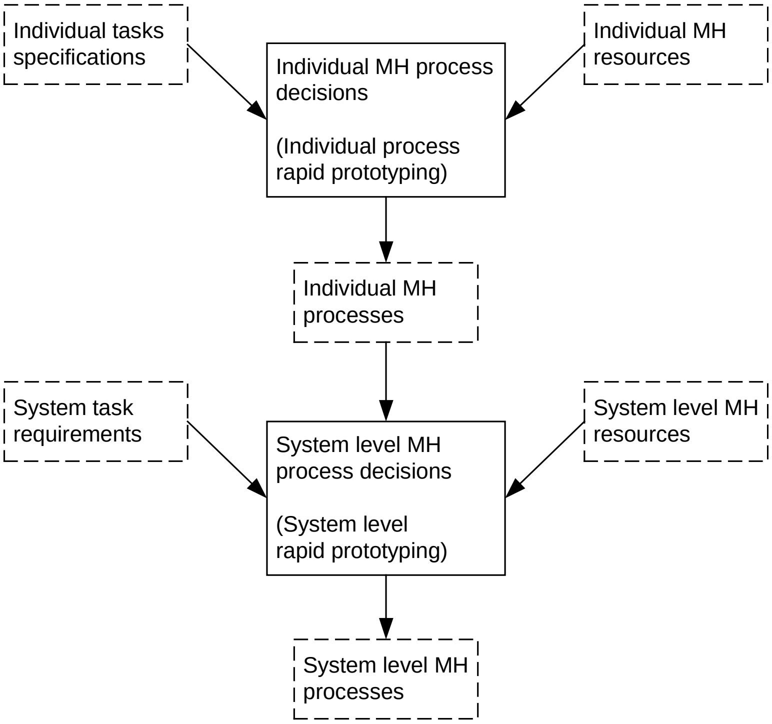


Figure 1. Overall procedure for material handling task requirements.

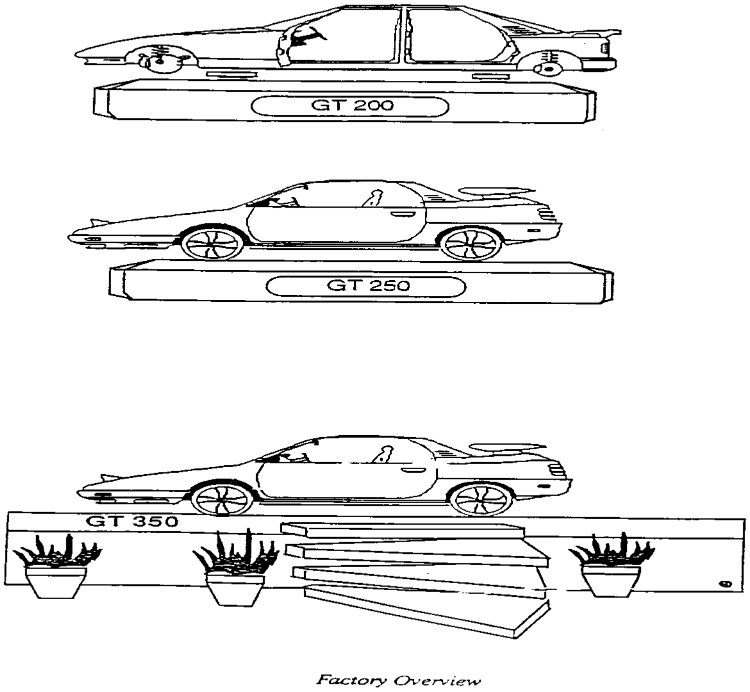


Figure 2. CMW Products [McKa 91]

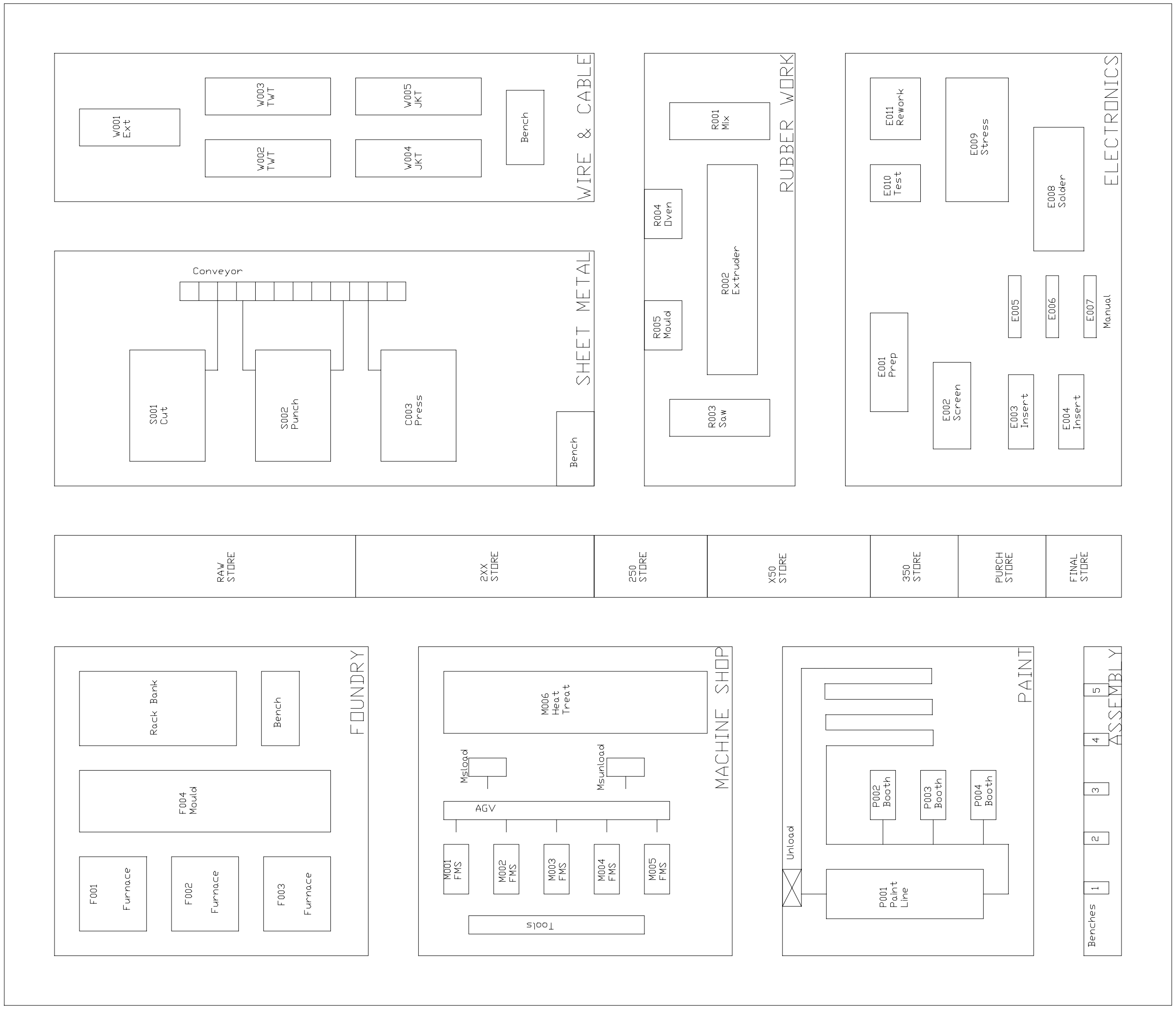


Figure 3. Floor Plan of CMW [McKa 91]

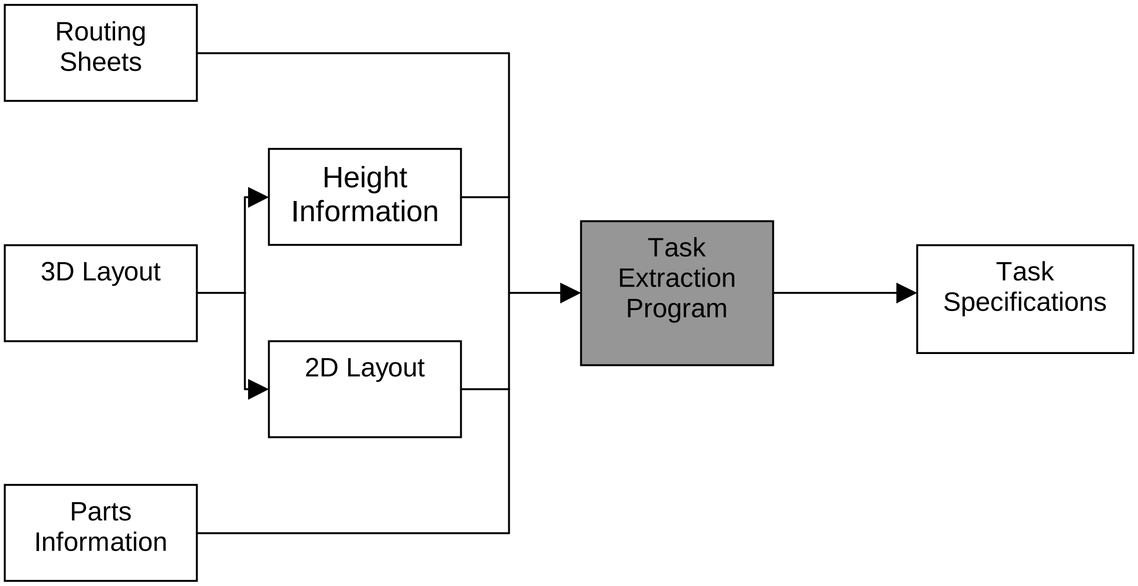


Figure 4. Automatic Extraction of Task Specifications