Chapter 11
Designing and Planning of Material Handling Systems for Mass Customization

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Abstract Mass customization (MC) involves the challenge of high product proliferation and frequent production volumes change. Flexible manufacturing has been treated as the main solution for these challenges. However, without a flexible material handling system (MHS), flexible manufacturing cannot be implemented successfully. Therefore, the designing and planning of the flexible MHS has attracted intensive research. This chapter first reviews different types of MHS in MC. In order to evaluate the performance of MHS, qualitative and quantitative measures are proposed. Then a detailed designing and planning of a flexible MHS using free-ranging automated guided vehicle (AGV) with an indoor local position-

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ing system (LPS) is illustrated. As a case study, the layout of the proposed flexible MHS in the apparel industry is designed. Then to assess the effectiveness of the proposed flexible MHS, Monte Carlo simulation and analytical models are formulated to compare its operational performance with that of the fixed-track systems commonly used in the apparel industry. Economic feasibility analysis is also included. Based on our analysis, the proposed flexible MHS has potential advantages over the fixed-track system in an MC environment.

Abbreviations

AGV	Automated guided vehicle
AS/RS	Automated storage/retrieval systems
ATCF	After-tax cash flow
AVT	Average time in the system
BTCF	Before-tax cash flow
CT	Cycle time
CV	Coefficient of variation
FIFO	First in first out
FRAGV	Free-ranging automated guided vehicle
IRR	Internal rate of return
J-Eton	Joined Eton
LPS	Local positioning system
LWS	Length of the workstation
MACRS	Modified accelerated cost recovery system
MARR	Minimum attractive rate of return
MC	Mass customization
MCE	Manufacturing cycle efficiency
MHS	Material handling system
PWC	Practical worst case
RFID	Radio frequency identification
SJ-Eton	Simply joined Eton
TH	Throughput quantity
TSS	Toyota System-Style
TTD	Total transportation distance
UK	United Kingdom
UPS	Unit production system
USB	Universal serial bus
VAE	Value added efficiency
WIP	Work in process

11.1 Introduction

MC has made considerable inroad in a number of industries such as the hospitality industry, the information industry, and particularly the manufacturing industry (Silveira *et al.* 2001). The net result of MC has significantly increased the variety of products and the frequency of changing volumes of demands. This proliferation of variety has put substantial stress on the manufacturing system in terms of the ability to flexibly and rapidly respond to customer demands. Therefore, to realize mass customization, the flexible manufacturing system has to be deployed (Bock and Rosenberg 2000, Chakraborthy and Banik 2006, Cheung 2005, Xiao *et al.* 2001). As one of the critical components of flexible manufacturing systems, the flexible material handling system plays a strategic role in the implementation of flexible manufacturing systems (Beamon 1998, Jawahar *et al.* 1998). According to Sule (1994) and Tompkins *et al.* (2002), material handling accounts for 30–75% of the total cost of a product, and efficient material handling can be responsible for reducing the manufacturing system operations cost by 15–30%. However, inadequately designed MHS can indeed interfere severely with the overall performance of the production system, and lead to substantial losses in productivity and competitiveness, and to unacceptably long lead times (Chakraborthy *et al.* 2006). This makes the subject of material handling increasingly important. In addition, all the complexity of manufacturing is passed on to the material handling system. Therefore, the designing and planning of the flexible material handling system is considered as an important issue in production planning and control in MC.

There are many material handling systems in the real world. Each system has its own pros and cons for particular applications. Therefore it is crucial to select the proper type of material handling systems for MC. For instance, with the advent of barcode and radio frequency identification (RFID), material movement can be tracked effectively and automatically. As a consequence, it makes sense for MHS supporting MC to be moving towards automation. To carry out the designing and planning of flexible material handling systems, several quantitative performance measurements are needed to guide the designing process. At the same time they can also be used to verify the performance of the entire production system for MC in the case study. In this chapter, first in Section 11.2, we will show different kinds of MHS which can support MC. The pros and cons of these systems are discussed to select the proper type of MHS for MC. Several qualitative and quantitative performance measurements are also provided to guide the designing process. Then the detailed designing and planning of a flexible MHS using free-ranging AGV with an indoor LPS is illustrated. In Section 11.3, as a case study, the application of existing automatic MHS for an apparel manufacturer is discussed. To assess the effectiveness of the proposed flexible MHS, its performance is compared with that of a fixed-track system such as the Eton System already implemented successfully in the apparel industry. An analysis showing the potential advantages of free-ranging MHS over the fixed-track MHS will be presented. Finally, recommendations and conclusions are presented in Section 11.4.

11.2 Designing and Planning Considerations on Material Handling Systems for Mass Customization

To identify the proper MHS for MC, different flexible MHSs are reviewed and compared using qualitative analysis. We find that the free-ranging MHS has potential advantages for MC. To clarify the potential advantage, quantitative analysis is necessary. Therefore, several performance measures of flexible manufacturing are proposed. Finally, detailed designing and planning considerations of a flexible MHS using free ranging automated guided vehicle with an indoor LPS are illustrated.

11.2.1 Different Flexible Material Handling Systems

Generally, the determinant of a material handling system involves both the selection of material handling equipments and the assignment of material handling operations to each individual piece of equipment (Sujono 2007). Moreover, the scheme of the assignment highly depends on the material handling equipment. Hence, we can classify material handling systems mainly by the type of the material handling equipment.

In the literature, material handling equipments are classified into main groups of industrial trucks, conveyors (*e.g.*, Figure 11.1), fixed-track automated guided vehicles (*e.g.*, Figure 11.2), cranes, industrial robots, and automated storage/retrieval systems (AS/RS) (Kim and Eom 1997). Actually, manual material handling is still fairly popular in many industries such as the electronics manufacturing industry and the apparel industry. Since manual material handling, industrial trucks, and cranes involve human beings, we can group them together as the manual-type MHS. The industrial robots and automated storage/retrieval systems operate with a fixed position. Therefore, they are classified as fixed-point MHS. Recently artificial intelligence has been applied to material handling. The conceptual free-ranging AGV MHS was proposed in (Dai *et al.* 2008). Other classes of MHS are presented in Table 11.1.

Table 11.1 Summary of material handling systems

System type	Examples
Manual-type MHS	Manual handling, industrial trucks, cranes
Conveyor MHS	Conveyor belt, roller conveyor
Fixed-point MHS	Industrial robots, AR/RS
Fixed-track AGV MHS	Lift AGV, tugged AGV
Free-ranging AGV MHS	Free-ranging MHS

Figure 11.1 Conveyor belt of conveyor MHS

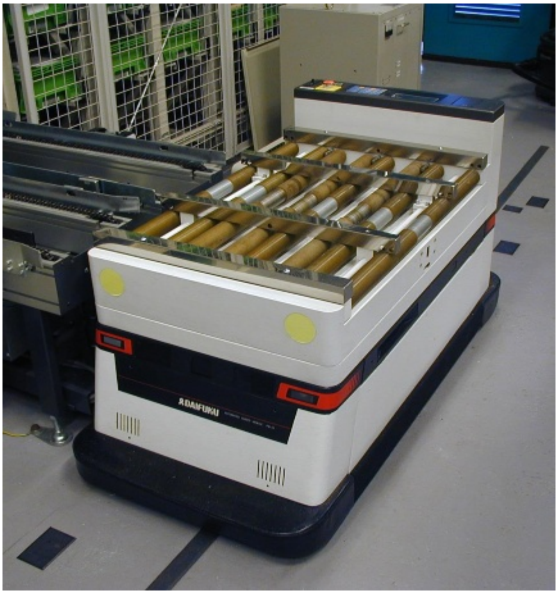

Figure 11.2 Fixed-track AGV MHS

11.2.2 The Designing and Planning of Flexible Material Handling Systems

After reviewing the flexible MHS, it is interesting to select and design the proper MHS for MC. Evaluation can then be conducted according to the proposed performance measures.

11.2.2.1 Qualitative Performance Comparison of Material Handling Systems

There is much literature focusing on the evaluation and selection of material handling systems (Fonseca *et al.* 2004, Rao 2006, Rembold and Tanchoco 1994). Different models have been formulated to compare the performance of material handling systems. In them, MHS are classified according to the flexibility and speed they provided to the production system. Such classification is presented in Figure 11.3. Their performances in setup cost, operating cost, quality, and reliability are presented as well. When the handling process becomes complicated, manual MHS is easy to make mistakes, and therefore the process reliability will be low. Moreover, in the manual MHS, materials are handled by bundle, and it may be easy to cause material defects. As a consequence, the product quality will be affected.

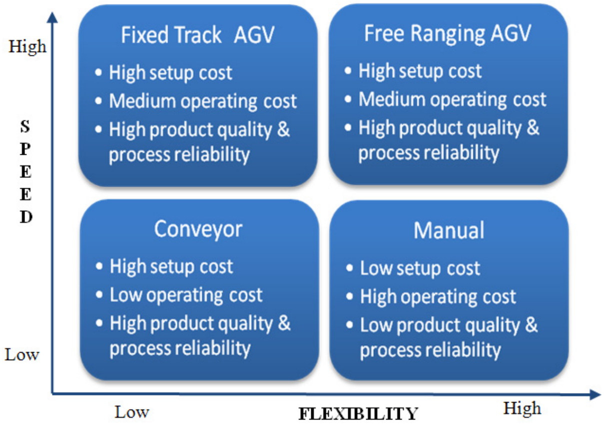

Figure 11.3 Summarized comparisons of the MHS

11.2.2.2 Performance Measures

Manufacturing system effectiveness is a function of manufacturing cycle efficiency, value added efficiency, work in process, average time in the system, and through-put quantity. These are classical performance measures of MHS. Workstation utilization and the total transportation distance can sufficiently explain the underlying reasons for the improvement of MHS. Hence they are also included as efficiency determinant factors, and presented in the following terms.

Manufacturing Cycle Efficiency (MCE)

MCE is a traditional measure of the manufacturing process. It is defined as the ratio of the time in actual production and setup process over the total time in the production area (Fogarty 1992). The higher the ratio, the higher the percentage of time spent in the workstations. The definition is shown in the following formula.

$$MCE = \frac{S + R}{S + R + W + M} \tag{11.1}$$

Where S denotes the total setup time, R denotes the total running time, W denotes the total waiting time, and M denotes the total material handling time.

Value Added Efficiency (VAE)

VAE measures the percentage of time added to a product during the production process. It is defined as the ratio of total run time to the total manufacturing time (Fogarty 1992) as shown in the following formula:

$$VAE = \frac{R}{S + R + W + M} \tag{11.2}$$

Although VAE looks similar to MCE, when the setup time is relatively large, improving MCE not always leads to significant productivity improvement. Therefore, VAE is valuable when measuring the performance of the manufacturing system, particularly the system whose setup time is changed.

Work In Process (WIP)

WIP is defined as the inventory between the start and end points of a product routing, and it is commonly used as a criteria to assess manufacturing systems (Fogarty 1992, Viswanadhamand Narahari 1992). It has significant effect on the inventory cost and the capability of flexibly and quickly responds to customers requirements.

Average Time in the System (AVT)

AVT is the long-term average time of a part spent in the system from entering the loading station to departing the unloading station. This can be used to measure the speed of the response to a new order (Sameh and Mike 1998).

Throughput Quantity (TH)

TH is often simply referred to as throughput or production volume and it is the number of jobs completed in a given period of time. This may also be denoted by production rate (Beamon 1998; Egbelu and Tanchoco 1984). According to Littles' law, the relationship between TH, WIP, and the cycle time CT is defined as:

$$TH = \frac{WIP}{CT} \tag{11.3}$$

When comparing the performance of manufacturing systems, we often need to consider the performance in the practical worst case. The TH of the practical worst case TH_{PWC} of given WIP level w is defined as follows (Tompkins *et al.* 2002):

$$TH_{PWC} = \frac{w}{W_0 + w - 1} r_b \tag{11.4}$$

$$W_0 = r_b T_0 \tag{11.5}$$

Where W_0 denotes the critical work in process, r_b denotes the bottleneck rate, and T_0 denotes the raw process time.

Workstation Utilization

Workstation utilization is defined as the fraction of actual operating time to the total available time (Viswanadham and Narahari 1992). It reflects the average efficiency of the workstations being used in the production line. In the apparel industry, the order size is relatively small. Different products often require different sequences of production processes. Due to the fixed-track property of Eton Systems, it is necessary to change the locations of the machine to suit a new product. Relocating machines takes time. Therefore, it would decrease the productivity of the entire system. However, since the free-ranging AGV (FRAGV) has the property of free path, there is no need to relocate the workstation for launching a new order.

Here, we assume that all these workstations are never idle and never fail before finishing an order. Furthermore, the production line is well balanced. As we want to compare the performance of the free-ranging MHS and fixed-track systems, the formulation below will include the relocation of the workstation. During the comparison, we will set the relocation time to zero for the free-ranging MHS. Therefore, in this formulation, before launching a new order, it is necessary to clear the production line and relocate the workstations. It is interesting to note, for the purpose of improvement of productivity, that the relocation for launching a new product can be started while some of the work for the existing product is being finished. In our case, we let l be the number of workstations finishing the work for the existing product. Therefore, the average time of each order spent in production is $T_C(Q+[NP_L]-l)+T_R+T_S$. However, the effective time is only QT_C. Therefore, the effective workstation utilization can be formulated as follows:

$$U = \frac{QT_C}{T_C(Q+[NP_L]-l)+T_R+T_S} \tag{11.6}$$

Where P_L denotes the percentage of workstations loaded in an order. Then $[NP_L]$ denotes the total number of workstations required for the new order. Where Q denotes the order size, T_C denotes the cycle time, T_S denotes the setup time, and T_R denotes the total machine relocation time.

Total Transportation Distance (TTD)

TTD, one of the most frequently used criteria for evaluating material handling systems (Sedehi and Farahani 2009), is defined as the weighted sum of material flow distances between different workstations or departments. Suppose the transportation speed is the same and the requirements for the workstation are also the same in different systems. In this case, the minimum material flow distance is valuable for enhancing the utilization of the entire system, reducing the throughput time and the WIP. As a result, this improves the capability of responding to customers' requirements quickly. A detailed analytical formulation of the TTD of the free-ranging MHS and fixed-track systems is given in Dai *et al.* (2008).

11.2.2.3 Structure of the Free-ranging Material Handling System

The main concept of the free-ranging MHS is that it can support free-ranging material handling rather than fixed path material handling. In order to achieve the free-ranging property, the following structure and subsystems are required:

Local Positioning System (LPS)

To support the function of the free-ranging AGV, an indoor local positioning system is required to estimate the absolute position information for the free-ranging AGV. A potentially cost-effective and accurate ultrasonic positioning system was been proposed for navigating AGV by Lee, Chan and Dai in 2008 in an unpublished article. In the ultrasonic positioning system, emitters of ultrasound and radio frequency are placed on the ceiling of the plant, while receivers are placed on the free-ranging AGV. Since the radio frequency propagates much faster than the ultrasound, the synchronously transmitted signals from the same emitter will arrive at the receiver at different times. Based on the time difference of propagation for the radio frequency and the ultrasound, one can determine the distance between the emitter and the receiver. A multilateration method can be used to figure out the position of the free-ranging AGV with multiple transmitters placed at different locations. Many algorithms such as the Karman filter and the particle filter may also be applied to improve the tracking and navigation performance.

Central Controller

A central controller is widely used in the manufacturing industry. In the free-ranging MHS, the central controller is designed for several purposes. Firstly, it can monitor and control the movement of the free-ranging AGV and the entire manufacturing system. Secondly, it may be used to identify failures or problems as well as to optimize the production system. Thirdly, it gives orders to the loading module in workstations by radio frequency to load the materials and at the same time dispatch jobs to workstations. Fourthly, it stores the information of the product or the material which is collected by the RFID.

Free-ranging AGV (FRAGV)

Basically, the function of the AGV is similar to that of a truck. However due to the limited space of paths in the MHS, it is vital for the FRAGV to have the capability of turning 90° to change the orientation in the path without changing its position. Therefore a special design should be adopted. One of the easy ways to provide this tight quarter turning is to use two independent motors for the left and right wheels of the FRAGV. Furthermore, this vehicle is controlled by the central controller discussed above. This can be accomplished by first determining the location of the FRAGV by the LPS. Second, the FRAGV transmitters send this position information to the central controller. Finally, the central controller controls the speed and direction of the FRAGV. The power supply of the motors is provided by a rechargeable battery.

Workstation

In this system, the workstation should be equipped with a loading and unloading system for the FRAGV to bring the material in and out of it. The tray should be used to contain the parts. To track the material flow, RFID or a barcode may be used. To enhance the throughput, a buffer that can hold several trays is used.

Battery Charging/Changing Station

A supportive station should be provided for the FRAGV to charge batteries and exchange charged batteries with the empty ones. To facilitate the automated charging or exchanging of batteries, the FRAGV is required to stop near the battery charging/changing station quickly and accurately. Therefore, a specially designed mechanical track is placed near the station.

11.2.2.4 Methodology of the Free-ranging Material Handling System

The previous section describes the main structure of the free-ranging MHS. In this section, we will discuss the operating methodology of the free-ranging MHS.

1. *Order loading:* when an order has been placed in the production line, the central controller would generate a production plan based on the production process, the bill of materials, the size of the order, and the status of the production line. From this production plan, the material flow requirements will be generated.
2. *FRAGV:* a dispatching central controller will select the FRAGV based on the material flow requirements and the status of the FRAGV such as availability and location.
3. *Routing:* a central controller determines the optimal routing for the FRAGV based on the location and the destination as well as the traffic condition.
4. *FRAGV movement control:* aided by the LPS, the central controller would be able to track the movement of the FRAGV. Then, the central controller chooses the optimal speed and direction for the FRAGV. To reach the planned speed and direction, the central controller controls the input currents to the motors in the left and right wheels.
5. *Traffic control:* to avoid congestions and collisions, the central controller has to coordinate the movement of the FRAGV. LPS and scheduling algorithms play a vital role in this step. Control is realized through the wireless communication with radio frequency.
6. *Part loading and unloading:* once the FRAGV reaches the designated workstation, the operation of loading and unloading takes place. This operation is controlled and monitored by the central controller, aided by the LPS and the RFID technology.
7. *Material tracking:* RFID can be used to track the material flow.
8. *Rerouting operation:* this is a potential advantage of the free-ranging MHS. Sometimes the production line experiences unexpected change of the status in

workstations or FRAGVs, for example, the breakdown of a workstation or FRAGV. In such an instance, the central controller can modify the dispatching and routing order for the FRAGV. The failed FRAGV will be pulled back to the AGV charging and storage station to avoid traffic congestion.

11.3 Industrial Application for the Apparel Industry

The apparel industry generated a total revenue of 1.5 trillion US dollars in 2006 (Datamonitor 2007). It has the properties of small order size and rapidly changing customer demands. Therefore it is extremely demanding for mass customization (Lee and Chen 1999, Le *et al.* 2002). However, due to the intensified challenge of mass customization and increasing labor cost, the apparel industry in the advanced countries or areas has been facing a steady decline recently (Chin *et al.* 2004). In order to streamline their production cycle to better respond to consumers' demand and at the same time to save cost with improving quality, apparel manufacturers are starting to seek new business and manufacturing practice and strategies, among which the improvement of the designing and planning of material handling systems ranks first (Witt 1995).

11.3.1 Existing Material Handling Systems for the Apparel Industry

There is extensive research on automatic handling and manipulation of textile products in the apparel industry. A robotic system is developed for textile-like materials handling in (Paraschidis *et al.* 1994) from the perspectives of handling operations based on version and force/torque sensing. A flexible material handling system with wired AGV, which transports garments from the silkscreen process to the fold-and-pack area, and the conveyor belt, which delivers the boxed goods from fold-and-pack area to the shipping area, have been designed to increase throughput and product quality (Aldrich 1995). The "walking floor", which is a sequentially operated reciprocating floor slat conveyor with typical actuation through three hydraulic cylinders, provides an opportunity to improve the material handling throughput, as reported by Beason (1999). The unit production system (UPS) that transports the material by a hanger-like carrier, increases the efficiency and reduces the WIP level of apparel manufacturing traditional bundling systems (Hill 1994). There are two classical UPS in the market: one is the TUKAtrack Information Tracking System from the United States and the other is the Eton system from Eton Systems in Sweden. Other material handling solutions in the apparel industry include Toyota System-Style (TSS) quick response methods with garments passed by hand, the manual overhead sewing production line in UK-based Peter Ward, and Magic Tube for garment production, handling, warehousing, and transportation systems in Salpomec Ltd. However, Eton Systems from Sweden remains the market leader in the modern apparel industry (Tait 1996).

The Eton system, designed by Inge Davidson, the founder of Eton Systems Inc., is a UPS with computerized overhead conveyer and individually addressable workstations which transports the materials by a hanger-like carrier to increase the efficiency and reduce WIP level of apparel manufacturing. Figure 11.4 shows the appearance of the Eton system. The newest generation of Eton systems is the Eton 5000 Syncro. The main idea of the Eton system is to use a hanger-like carrier to transport the material through the production line. It replaces manual material transportation, which occupies valuable skillful operators' time, by an automated hanger system so that operators can concentrate on their jobs. Figure 11.5 presents the schematic layout of Eton systems. Figure 11.6 presents the layout of two commonly used Eton systems: the simply joined Eton (SJ-Eton) and the joined Eton (J-Eton). If the workstation is assigned a task, the carrier will hand the material to the branch of the workstation, otherwise, the material will be handed to the next workstation directly by the headline. A detailed illustration of Eton systems can be found on the company's homepage (www.eton.se). To identify the proper MHS for mass customization in the apparel industry, the performance of these MHSs is qualitatively compared in Table 11.2. We can observe that the UPS and the MHS using fixed-track AGV outperform other MHSs, which is why these two systems are fairly popular in practice.

Figure 11.4 The Eton system from Sweden

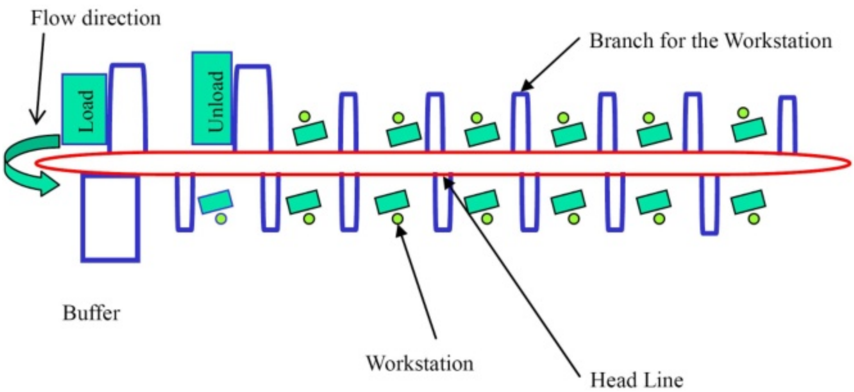

Figure 11.5 Schematic layout of a basic Eton line

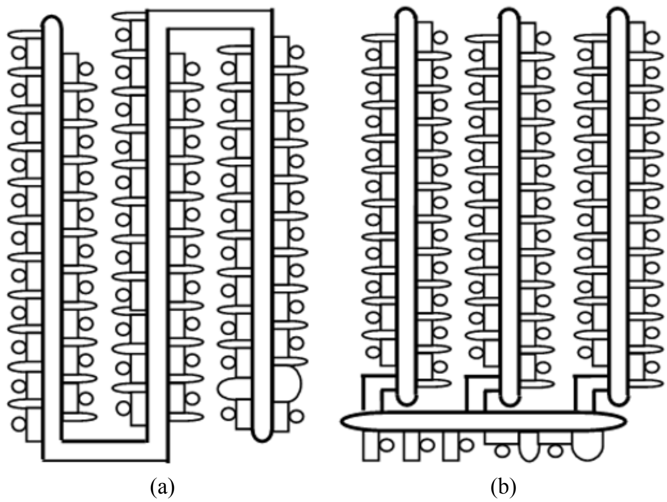

Figure 11.6 Configuration of the simply joined Eton system (a) and the joined Eton system (b)

Table 11.2 Summary of material handling systems

System	Flexibility	Speed	Setup cost	Operating cost	Product quality and process reliability
Manual overhead sewing line	High	Low	Low	High	Low
Conveyor belt	Low	High	High	Low	High
Toyota system-style	Low	High	Medium	Medium	High
Progressive bundle	Low	Low	Low	Medium	Low
Unit production system	Medium	High	High	Low	Medium
Fixed track AGV	Medium	Medium	High	Low	High

11.3.2 System Layout Design

Facility layout design has been a very active research area in the past four decades; many optimization models are reviewed in Beamon and Chen (1998), Chittratanawat and Noble (1999). However, most of the models assume that information regarding production quantity and routing path of different products is known in advance. In the apparel industry, the demand is changing quickly and is very difficult to forecast; so in this paper we only focus on constructing the conceptual layout of the free-ranging MHS mainly from the perspectives of approximated system performance and safety. Considering the space dominated by the fixed-track system, we design the layout for the free-ranging MHS, as presented in Figure 11.8. In order for the proposed system to operate properly using a central controller, local positioning system and the FRAGV, we need a special consideration on the system layout, such as safety issues. To avoid the interference of human traffic in our free-ranging MHS, the moving paths for AGVs and humans are separated in our design. As shown in Figure 11.7, the loading and unloading workstations are positioned at the top. The AGV charging station is located at the bottom and the workstations are placed in the center. Each workstation comprises a loading area, which is denoted by a small rectangle, and an operating area, which is denoted by a large rectangle. The workstations are then grouped into subgroups, and a path for the FRAGV in the center connects all subgroups together. The FRAGV can only access the path in the subgroups and the path con-

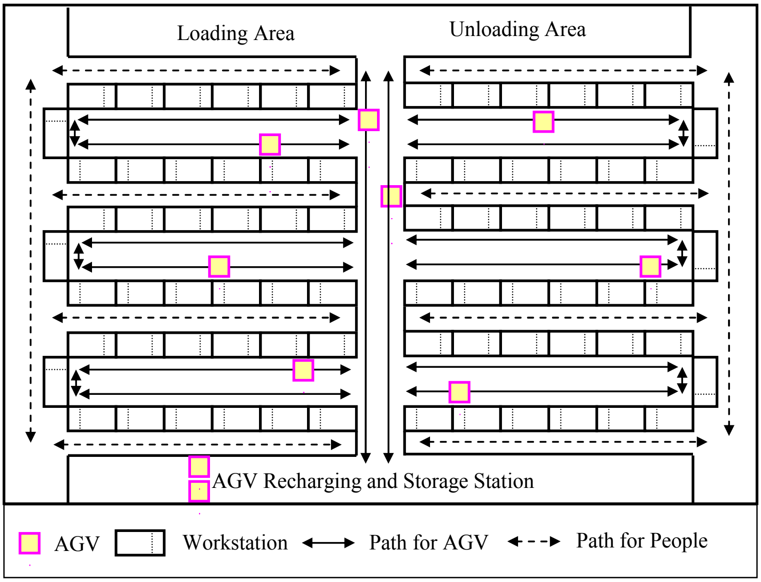

Figure 11.7 Schematic layout of the free-ranging MHS

necting subgroups to transport the material among workstations. The path for the FRAGV can hold two bi-directional paralleling FRAGVs. As a result, once one FRAGV is broken, the other can cross the path to ensure the continuous material handling and avoid congestion due to the specially designed FRAGV, which can flexibly turn 90°. The corridors between the subgroups can only be accessed by the workers. In this case, this design separates people and FRAGVs for safety reasons. Due to the free path property, machines with similar functions can be arranged by function, product, or hybrid layout for easy maintenance and better resources sharing.

11.3.3 Potential Advantages of the Free-ranging Material Handling System

The Monte Carlo simulation approach is adopted for the following reasons. Maione *et al.* (1986) assume that the material handling time, including the traveling and loading/unloading time, is negligible compared to the processing time. However, in apparel manufacturing, the processing time is relatively short, which makes the proportion of material handling time higher. For example, in many sewing factories, 80% of the production time is spent on material handling and only 20% is spent on sewing; thus, it is necessary to take the material handling time into the performance analysis (Wong *et al.* 2005). Therefore, analytical models become invalid and simulation is used to assess the performance of manufacturing systems and material handling systems (Lu and Gross 2001, Qiao *et al.* 2002, Savory *et al.* 1991, Smith 2003). Furthermore, in the apparel industry, since the number of workstations required is usually large, it is unpractical to formulate the simulation using traditional software such as SIMAN and ARENA; thus, discrete time Monte Carlo simulations using MATLAB are formulated to do the comparative study.

To construct the simulation models for the free-ranging MHS and fixed-track systems, several assumptions are required to facilitate the comparative analysis:

1. The processing times follow identical independent normal distributions, and the production line is well balanced.
2. The first workstation is also busy and no preemptive failures occur in the entire system.
3. The speed of handling is fixed no matter whether the FRAGV or carrier is loaded or not.
4. The number of FRAGV and carriers is enough for each order.
5. First in, first out (FIFO) rule is used for all workstations.
6. Workstations with short transportation distance have high priority to be loaded.

Discrete time Monte Carlo simulations using MATLAB are formulated to do the comparative study. This entails the following steps:

1. Given the number of workstations n and the loading percentage P_L, find the minimal number of subgroups. Assign the tasks to the workstations and then figure out the transportation distance d_j from workstation $j-1$ to workstation j.
2. Generate the order size with random variables Q and the service time at workstation j with random variables S_j. Both variables follow normal distribution. When launching a new order, set the starting service time of the first entity $SS_{1,j}$ as the finishing service time of the last order FS_{Q,nP_L} plus the setup time and the relocation time.
3. If the queue length of the workstation j is larger than the designed buffer size C, denoted by $FS_{i,j-1} + d_j / v < FS_{i-C,j}$,
and then $FS_{i,j-1} = FS_{i-C,j} - d_j / v$, $SS_{i,j-1} = FS_{i,j-1} - s_{j-1}$,
and otherwise, $SS_{i,j} = \max(FS_{i-1,j}, FS_{i,j-1} + d_j / v)$, $FS_{i,j} = SS_{i,j} + s_j$.

Collect the waiting time W and the total material handling time M, average time in the production line AVT, and the throughput $TH = Q/(FS_{Q.nP_L} - SS_{1,1})$ as follows:

$$W = \frac{1}{Q}\sum_{i=1}^{Q}\sum_{j=1}^{nP_L}(SS_{i,j} - FS_{i,j-1} - d_j / v) \tag{11.7}$$

$$M = \sum_{j=1}^{nP_L} d_j / v \tag{11.8}$$

$$AVT = \frac{1}{Q}\sum_{i=1}^{Q}(FS_{i,nP_L} - SS_{i,1}) \tag{11.9}$$

The other measures can be calculated by these parameters using the model that we defined in the previous section. Repeat from step 2 to ensure that all the measures are converged. Practical inputs of the simulation are shown in Table 11.3. The number of workstations indicates the scale of the production system. The loading percentage measures how many workstations needed for a product. These dimension parameters and speed are used to calculate the material handling time. The buffer size means how many pieces of material may be buffered in each workstation before the processing operation. Each simulation was replicated 200 times with a study period of 24 running hours *per* day to ensure convergence. As a result, in all the performance measurements, the coefficient of variation (CV) is less than 5%.

Figure 11.8 compares the manufacturing system effectiveness of the free-ranging MHS and fixed-track MHSs in flexible manufacturing of small order sizes. The improvement is computed comparing the measures obtained in the free-ranging MHS and the better measures in both the SJ-Eton system and the J-Eton system. We can see that the free-ranging MHS improves the VAE by over 50%, the WIP and the AVT by over 20%, the MCE by over 10%, and the TH by over 3% in producing small orders. The underlying reason is that the free-ranging MHS shortens the setup time and material handling time and therefore the waiting time.

Table 11.3 Input parameters for the simulation example

Input parameters	Value
Number of workstations	60
Processing time (s)	$5 + N(20, 5)$[3]
Order size	$N(200, 20)$
Conveyor speed (m/s)	1.2
Free-ranging AGV speed (m/s)	1.2
Loading percentage	80%
Length of the workstation: LWS (m)	2.2
Width of the workstation (m)	1
Width of the corridor (m)	1
With of the headline (m)	0.8
Length of the workstation branch (m)	1.5
Height of the workstation branch (m)	0.8
Length of the loading and unloading station (λL_{WS})	$3 L_{WS}$
Subgroup size in Eton systems	21
Subgroup size in the free-ranging MHS	13
Buffer size in Eton systems	8
Buffer size in the free-ranging MHS	2
Total setup time (s)	900
Total relocation time (s)	900

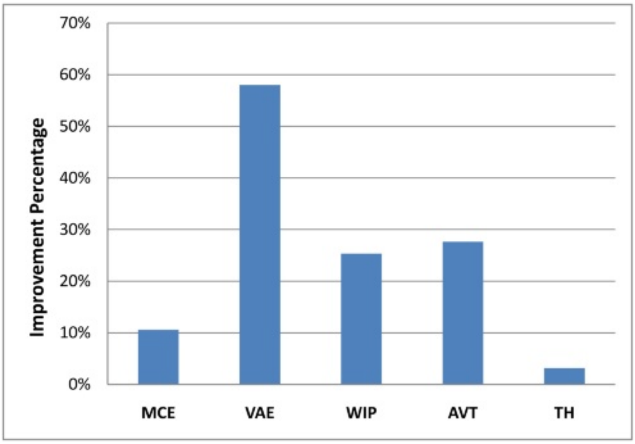

Figure 11.8 Monte Carlo simulation results of comparing manufacturing system effectiveness

Although the free-ranging MHS only improves the TH slightly, it improves the TH in the practical worst case significantly. Based on the simulation results, using (11.4) and (11.5), we can find that the TH in the practical worst case for the SJ-Eton system, the J-Eton system, and the free-ranging MHS are 0.0192 unit/s,

[3] N(20, 5) indicates a normal distribution with a mean of 20 and a standard variance of 5

0.0195 unit/s, and 0.0227 unit/s, respectively; therefore the improvement of THC_{PWC} is 16.6%. Moreover, the setup time of the free-ranging MHS is much shorter than that of the Eton systems, so the free-ranging MHS can produce much faster than Eton systems at significantly lower inventory level.

Based on the industry example presented in Table 11.3, the performances of the workstation utilization and the total transportation distance are compared to evaluate the effectiveness of the free-ranging MHS in addressing product proliferation or customization. Results for the workstation utilization comparison are shown in Figure 11.9. For small order sizes, the free-ranging MHS improves the work station utilization by over 10%. The improvement percentage increases as the loading percentage or the order size decreases. This indicates that the free-ranging MHS can produce more at the steady state than Eton systems, and it is extremely effective for addressing product proliferation in the apparel industry, especially when there are multiple orders loaded in the same production system.

Figure 11.10 compares the total transportation distance of the free-ranging MHS and Eton systems under different numbers of workstations and loading percentages. The number of workstations denotes the scale of the manufacturing plant, and the loading percentage denotes different products. We may conclude that the free-ranging MHS shortens the total transportation distance in about 68% under high product proliferation in different manufacturing plants. Therefore it could shorten the material transportation time and then the waiting time. There are two underlying reasons for these results. First, in Eton systems these parts need to pass through the headline in the central loading section, which induces extra traveling distance into the system. However, in the free-ranging MHS, the FRAGV can turn in both directions on the main path. As a result, these parts do not need to travel the full main path to return to the loading station. Second, there is no vertical material flow distance in the free-ranging MHS. The variation in the improvement is due to the fixed-track in Eton systems. In Eton systems, parts are required to go through the entire headline no matter how many workstations are loaded. The handling distance in the headline depends on the number of workstations in the manufacturing plant.

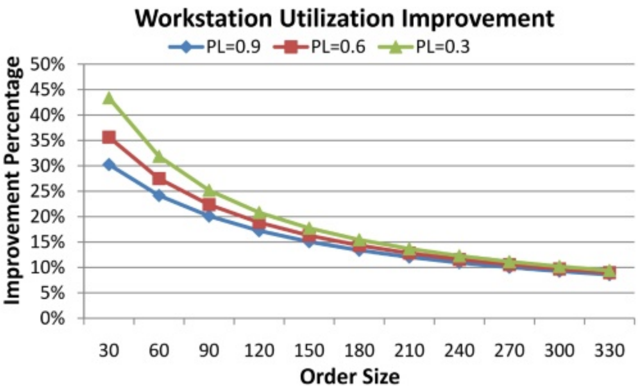

Figure 11.9 Workstation utilization improvement under different loading percentages

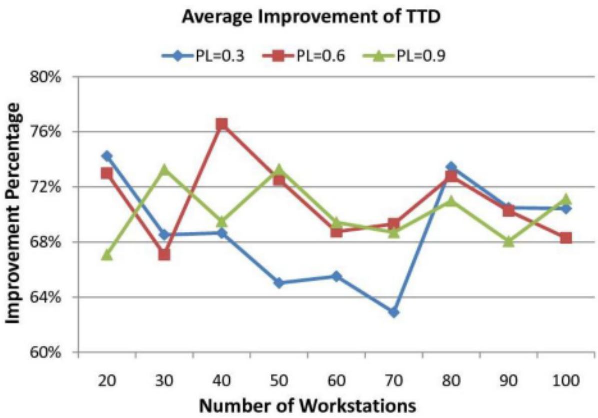

Figure 11.10 Total transportation distance improvement under different loading percentages

11.3.4 Economical Feasibility Analysis on Free-ranging MHS

From the study above, we observe that the flexible free-ranging MHS has potential advantages in the performance measures over the fixed-track MHS. However automatic MHSs are difficult to implement and operate. Therefore the cost–benefit analysis of these automatic MHSs is necessary. Moreover, it might be better to have a manual system that is very flexible with some extra personnel to match the throughput advantages of the free-ranging MHS without the associated machine setup and operating costs. Therefore, the economic feasibility analysis should be conducted by benchmarking performance on the manual MHS.

11.3.4.1 Cost Estimation of Adopting Automatic MHSs

Suppose that currently the manual system is used, and then the objective of the economic justification is to study the project performance of introducing automatic MHSs. To conduct the justification, it is necessary that several costs and benefits be estimated in advance.

Investment

The free-ranging MHS comprises FRAGVs, sensor station, workstation, battery changing/charging station, tracking system, software, and computer system. To estimate the investment of introducing the free-ranging MHS, costing of those components is necessary. A sample FRAGV has been developed in our study. Its cost breakdown is presented in Table 11.4. The total cost of the FRAGV is US $860. This estimation is conservative because actually the cost of the material may be discounted somewhat in mass production. The car manufacturing industry gross profit margin is about 20% in China. It is reasonable to set the gross profit margin of the FRAGV as 40%, and then the selling price of the FRAGV is US $1,204. Since each FRAGV may serve 2–3 workstations, the total number of FRAGVs in the numerical example with 60 workstations is about 25. Supposing there are 20% extra FRAGVs for replacement, the total number of FRAGVs is 30. Then, the total investment of the FRAGV is US $36,120. The sample software has not been developed yet and it may cost 20 Chinese software engineers 2 years to develop. The labor cost of each engineer is about US $15,000 *per* year. Therefore the total cost of the sample software is US $600,000. Suppose the market size is about 50, and then the cost of software is about US $12,000. The gross profit margin of the software industry in China is about 100%. Therefore it is reasonable to set the software gross profit margin as 300% here, and then the investment of the software is US $48,000. Table 11.5 presents the breakdown of the free-ranging MHS investment. The equipment value of the free-ranging MHS is US $158,674. Suppose the installation cost is 10% of the equipment value, and then the total investment of the free-ranging MHS is US $174,541. From the quote of the fixed-track system supplier, the investment including installation cost and training cost is about US $3,000 *per* workstation. Supposing there is a safety factor of 1.3, then the total investment of the fixed-track system is about US $234,000.

Table 11.4 FRAGV cost breakdown

Part	Items	Quantity	Total cost (US $)
Mechanical part	Geared motor and gearbox	2	462
	Battery	2	51
	Wheel and motor adapter	2	26
	Shelf and plastic panel	1	100
	Wheel		41
Wireless electronic part	Ardmino-min	3	13
	Ultrasonic sensor module	1	25
	Magnetic compass	1	49
	Radio frequency module	1	18
	USB transaction	1	6
	Motor control panel	1	19

Table 11.5 Free-ranging MHS investment breakdown

Part	Quantity	Total cost (US $)
FRAGV	30	36,120
Sensor station	60	3,354
Workstation modification	60	30,000
Battery changing/charging station	1	20,000
Tracking system	1	20,000
Software	1	48,000
Computer	2	1,200
Total		158,674

Labor Cost

According to a survey by Hill (1994), the fixed-track MHS such as the Eton system may reduce direct labor by about 9.7% compared with manual MHS; moreover, the ratio of the number of direct labor cost to the number of workstations is 82%. Therefore, the total number of direct labor in the fixed-track MHS is $600 \times 0.82 \approx 49$, while the direct labor cost in the manual system is $49 \div (1–9:7\%) \approx 55$. The number of direct labor cost in the free-ranging MHS is 49 too because the automatic principle in the free-ranging MHS and fixed-track MHS is similar. Suppose currently the labor rate is US $2.5 per hour and the fringe benefit as a percentage of payroll is 25%. Then the labor cost of each worker is US $6,500 *per* year. Therefore, the total annual direct labor cost of the manual system, fixed-track system, and the free-ranging system is US $357,500, US $318,500, and US $318, 500, respectively.

Maintenance Cost

In the manual MHS we assume that there is only one worker in charge of maintenance; according to the labor rate assumed above, the estimated annual maintenance cost is US $6,500. In fixed-track MHS, more work is necessary for the hanger-like carrier, the track, the tracking system, the software, *etc*. According to the data provided by the fixed-track MHS supplier, the annual maintenance cost is generally less than 1% of the total investment. Therefore it is reasonable to set the annual maintenance cost as $6500 + 23400/100 =$ US $8,840. Table 11.6 compares the maintenance activities in both fixed-track MHS and free-ranging MHS. Since the maintenance of the FRAGV and the routing system is much more complicated, we assume that the maintenance cost of free-ranging MHS is a factor of 4 comparing with that of fixed-track MHS. In this case, the maintenance cost in the free-ranging MHS is US $35,360 *per* year.

Table 11.6 Maintenance activities comparison in both fixed-track MHS and free-ranging MHS

Fixed-track MHS	Free-ranging MHS
Hanger-like carrier	Sensor station
Track	FRAGV
Tracking system	Battery
Software	Software
	Battery changing and charging station
	Tracking system
	Routing system

System Change Cost

When the product or the system layout changes, the manual MHS and the free-ranging MHS is flexible enough to address these challenges. However, the fixed-track MHS is not flexible enough, and therefore system change is necessary. In the system change process, parts are removed and then installed in another location;

moreover, the production is delayed. Therefore, we assume that the system change cost is twice the installation cost. According to Hill (1994), the installation cost accounts for 16.6% of the original value of the equipment, and then the system change cost is $2 \times 234000 \div (1 + 16.6\%) \times 16.6\% \approx$ US \$66,628.

Salvage Value

According to Hill (1994), the salvage value of the fixed-track system is 25% of the original value of the new equipment; moreover, as reported by the fixed-track MHS supplier, the useful life is at least 10 years. In the free-ranging MHS, the major parts are the FRAGV and the software. The FRAGV has a useful life of about 5 years because the motor and gearbox can usually work about 5 years. Since the electronic components usually do not fail in 5 years, we assume that the salvage value of the free-ranging system is about 20% of the original value of the new equipment.

Productivity Improvement

Productivity improvement may bring the benefit of a corresponding ratio of labor cost savings to match the throughput of the manual MHS. However, productivity improvement has no effect on the maintenance cost. According to users' feedback, fixed-track MHS generally can enhance the productivity by 30–40% and sometimes even 100%. Here we assume that the productivity improvement is 30%. From the potential advantages analysis in Section 11.3.3, the free-ranging MHS may enhance the productivity over the fixed-track MHS by about 3% under different order sizes. Therefore, free-ranging MHS may improve the productivity by about 33.9% over manual MHS.

All the material handling resources in these three systems are summarized in Table 11.7.

Table 11.7 Material handling resources

Items	Manual MHS	Fixed-track MHS	Free-ranging MHS
Total investment	0	US \$240,000	US \$174,541
Direct labor cost	US \$357,500	US \$318,500	US \$318,500
Maintenance cost	US \$6,500	US \$8,840	US \$35,360
Cost saving (productivity improvement)	0	US \$73,7500	US \$80,635
System change cost	0	US \$66,628	0
Salvage value	0	US \$58,500	US \$43,635

11.3.4.2 Capital Investment in Automatic Material Handling Systems

From the cost estimation above, if there is no system change, in fixed-track MHS, he annual cost saving is $375500 + 6500 - (318500 \div (1 + 30\%) + 8840) =$ US

$110,160. Similarly, in free-ranging MHS, the annual cost saving is US $90,776. Table 11.8 presents the incremental cash flow in automatic MHSs compared with manual MHS. A modified accelerated cost recovery system (MACRS) as a common method of accelerated asset depreciation is used. Based on the incremental cash flow, Tables 11.9 and 11.10 show the after-tax present worth analysis of fixed-track MHS and free-ranging MHS, respectively. The incremental cash flow is the before-tax cash flow (BTCF); after tax deduction, the after-tax cash flow (ATCF), which is used to evaluate the economic performance, is generated. Since these two systems have different useful life, the automatic MHS adoption project may compared by the internal rate of return (IRR) and payback years. Table 11.11 shows the justification results. Both fixed-track MHS and free-ranging MHS have an IRR larger than 15%; moreover, the reasonable payback years indicate a reasonable risk of the investment. This means that it is profitable and safe to adopt automatic MHSs. Currently the IRR of fixed-track MHS is larger than that of free-ranging MHS, which indicates that when there is no system change and the labor rate is US $2.5 *per* hour, the fixed-track MHS may have better economic performance.

Table 11.8 Incremental cash flow

Items	Fixed-track MHS	Free-ranging MHS
Capital investment	US $240,000	US $174,541
Annual cost savings (before taxes)	US $110,160	US $90,776
Salvage value	US $58,500	US $43,635
Useful life	10	5
MACRS property class	7	3
Corporate income tax rate	25%	25%
After-tax minimum attractive rate of return (MARR)	15%	15%

Table 11.9 After-tax present worth analysis of the fixed-track MHS

Year	BTCF (US $)	MACRS depreciation (US $)	Taxable income (US $)	Income taxes (US $)	ATCF (US $)
0	−234,000				−234,000
1	110,160	−25,079	85,081	21,270	88,890
2	110,160	−42,980	67,180	16,795	93,365
3	110,160	−30,695	79,465	19,866	90,294
4	110,160	−21,920	88,240	22,060	88,100
5	110,160	−15,672	94,488	23,622	86,538
6	110,160	−15,655	94,505	23,626	86,534
7	110,160	−15,672	94,488	23,622	86,538
8	110,160	−7,827	102,333	25,583	84,577
9	110,160		110,160	27,540	82,620
10	110,160		110,160	27,540	82,620

Table 11.10 After-tax present worth analysis of the free-ranging MHS

Year	BTCF (US $)	MACRS depreciation (US $)	Taxable income (US $)	Income taxes (US $)	ATCF (US $)
0	−174,541				
1	90,776	−43,631	47,145	11,786	78,990
2	90,776	−43,631	32,588	8,147	82,629
3	90,776	−43,631	71,389	17,847	72,929
4	90,776	−43,631	81,076	20,269	70,507
5	90,776	−43,631	90,776	22,694	68,082

Table 11.11 Economic justification results

Items	Fixed-track MHS	Free-ranging MHS
IRR	36.37%	33.47%
Payback years	3.5	2.9

11.3.5 Sensitivity Analysis on Adopting Automatic MHSs

Due to high product proliferation and MC, it is necessary for the production system to suit different products. Since fixed-track MHS is not flexible enough, system change cost will occur when the system layout or product changes. In this case, the economic performance of fixed-track MHS will be worse. Therefore, it is necessary to study this risk on different system change cycle times. Table 11.12 shows the sensitivity analysis results on different system change cycle times. From the table, we may observe that when the system change cycle time is no less than 4 years, fixed-track MHS may have better economic performance. However, when the system change cycle time is less than 4 years, free-ranging MHS may be more promising. Currently, the labor rate used is US $2.5 *per* hour. However, for a ong-term project, the labor rate often changes. Increasing the labor rate may affect the annual cost savings in adopting automatic MHSs and then affect the economic performance of adopting automatic MHSs. Therefore, it is necessary to study the project performance with different labor rates. Here, we assume that the system

Table 11.12 Sensitivity analysis on system change cycle times for adopting the fixed-track MHS

System change cycle time (years)	IRR	Payback years
1	17.61%	8.1
2	28.53%	4.6
3	32.10%	4
4	33.79%	3.9
5	34.59%	3.5
6	35.31%	3.5
7	35.59%	3.5

change cycle is 3 years. Table 11.13 presents the sensitivity analysis results on different labor rates. In the case where the system change cycle time is 3 years, when the labor rate *per* hour is no larger than US $1.5, automatic MHSs are not recommended to adopt based on the after-tax MARR of 15%. When the labor rate *per* hour is larger than US $1.5, both automatic MHSs are promising. However, when the labor rate *per* hour is less than US $2.5, fixed-track MHS may have slight potential economic advantages, and when the labor rate *per* hour is no less than US $2.5, free-ranging MHS may be more promising.

Table 11.13 Sensitivity analysis on labor rate when adopting automatic MHSs

Labor rate per hour (US $)	Fixed-track MHS		Free-ranging MHS	
	IRR	Payback years	IRR	Payback years
1,5	13.13%	> 10	9.26%	> 5
2	23.27%	6	21.97%	3.9
2.5	32.10%	4	33.47%	2.9
3	40.41%	3.2	44.22%	2.3
4	56.19%	2.1	64.38%	1.7
5	71.41%	1.6	83.48%	1.3
6	86.36%	1.3	101.96%	1.1
7	101.15%	1.1	120.06%	0.9
8	115.86%	1	137.91%	0.8

11.4 Conclusion

In the designing and planning of a flexible MHS for MC, there are some factors such as product variety and order size that should be considered. For example, if there is high product proliferation, with the availability of free-ranging MHS, free-ranging MHS would be a good choice for the apparel industry with small order size. In addition to the potential advantages analyzed above, the free-ranging MHS has other benefits:

1. Since there is no physical boundary between production groups, resources such as idle workstations can be shared by different production lines.
2. The efficiency and effectiveness of a production line with parallel workstations can be enhanced. The queue for parallel workstations can be shared, which ensures that parts will follow on a first come first serve basis. This can help the supervisor to quickly identify potential problems. Moreover, it facilitates the flexible real time rescheduling of FRAGV and workstations.
3. Due to the free-path property of FRAGV, similar functions can be grouped together for better resource sharing, which is convenient for expanding production capacity.
4. Like fixed-track MHS, the proposed free-ranging MHS can also improve the utilization of labor resources significantly by replacing manual material handling

by automated material handling through FRAGV. Parts are tracked by the attached RFID tags and therefore they may be taken off the production line anytime without messing up the parts' information in the central controller.

In conclusion, the detailed designing and planning of free-ranging MHS is presented for MC. As an illustration, to evaluate the effectiveness of the free-ranging.

MHS, Monte Carlo simulation and analytical models are developed to compare its performance with that of the fixed-track systems, which are widely used in the apparel industry. Our analysis shows that the free-ranging MHS has substantial potential advantages over the fixed-track systems in terms of manufacturing system effectiveness, workstation utilization, and the total transportation distance. Free-ranging MHS can streamline the manufacturing process, lower the inventory cost, and have the capability of fast responding to customer demands and flexibly suiting various products and volumes of orders. Due to product proliferation, this potential advantage is important in the apparel industry.

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