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Industry Case Study: Automated Material Handling System Design for TFT-LCD Production Lines using Axiomatic Design

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ABSTRACT

We present a new design of the automated material handling system (AMHS) in thin-film-transistor liquid-crystal-display (TFT-LCD) panel production lines, using Axiomatic Design (AD) Theory. The processing equipment for TFT-LCD has undergone significant improvement through technological innovations. However, AMHS equipment has not had much improvement and uses the same AMHS concept as used ten years ago. For our design, we first decomposed the current AMHS, particularly the Automated Guided Vehicle (AGV) system, to identify problems using the Independence Axiom. We discovered that functional requirements in the current system are strongly coupled by the design parameters. Moreover, system performance was highly dependent on unpredictable and uncontrollable events. Therefore, in our new design, we focus on decomposing the parameter-interdependencies and developing a system that is robust to unpredictable events. The simulation results confirm that the performance of the new design is far superior to that of the current system. We use the Information Axiom to evaluate improvements in the new system. Lastly, we determine the operational parameters using functional periodicity.

Keywords: Axiomatic Design, Material Handling, Flexible Manufacturing, LCD Production System, Complexity in AMHS.

1 INTRODUCTION

1.1 MOTIVATION

The thin-film-transistor liquid-crystal-display (TFT-LCD [*]) industry has been one of the fastest-growing industries in recent years. Manufacturing processes for LCD panels are similar to semiconductor device fabrication processes and therefore all process equipment is also similar. However, LCD processes are performed on the surface of a glass substrate (called *mother glass* or *glass*) instead of a wafer. Since the first mass production of LCD panels in the early 90's, the manufacturing technology, especially processing technology, has made significant innovations. During the early stage of the LCD industry, the size of the mother glass was about the size of the wafer. Now the size of the LCD panels are much larger and getting even larger with demand for large flat television and other monitors. The growth of the industry has been mainly led by processing technology innovation and the strong market demand. In particular, the processing equipment for the LCD has undergone significant improvement, making technology innovations possible. The role of theautomated material handling system (AMHS) in LCD production lines is becoming more important as the LCD panels get larger and as the production efficiency becomes a primary determinant of competitiveness. Therefore, LCD manufacturers are trying to adopt an efficient material handling method and new technology rather than linearly scaling up the existing systems.

[*] Since the TFT-LCD is the most popular technology deployed in a mass production system among the various LCD technologies, unless otherwise mentioned, LCD in this paper refers to the TFT-LCD.

In this paper, we present a new AMHS design for LCD production lines using Axiomatic Design Theory (AD), which is a design theory first introduced by Suh [1]. The main purpose of this paper is to elaborate how AD helped identify the problems in the current system and how we applied AD Theory to redesign for a new system. In this regard, our analysis presented in this paper focuses on improving the single most critical functional requirement in the system. The rest of the analysis and complete design processes can be found in [2].

1.2 DESIGN APPROACH

In developing a new AMHS, we particularly used AD over other design methodologies because AD logically directs a way to eliminate unnecessary complexities in the system. It has been known in the industry that performance limitations of the current AMHS are mainly caused by the complicated operational rules. Furthermore, the inefficiency of the AMHS is rooted from the non-robustness of the system. We discovered that the major design improvement efforts for the current AMHS were done through optimization techniques. However, due to the conflicting design parameters, the system improvement by searching for optimal parameters was minimal. According to the AD Theory, a design that violates the Independence Axiom – the functional requirements must always be maintained independent of one another by choosing appropriate design parameters – cannot be improved unless it is first made to satisfy the Independence Axiom. Therefore, our new design focuses on decomposing parameter-interdependencies and developing a system that is robust to unpredictable events. In addition, we focus on designing a system that does not have to be optimized in the traditional sense, and can simply use functional periodicity, as discussed later.

1.3 BACKGROUND INFORMATION

In order to process LCD panels, the mother glasses need to go through more than 200 different processing steps. These steps are categorized into four different processing stages: the TFT, color filter (C/F), cell, and module stage. The TFT and C/F

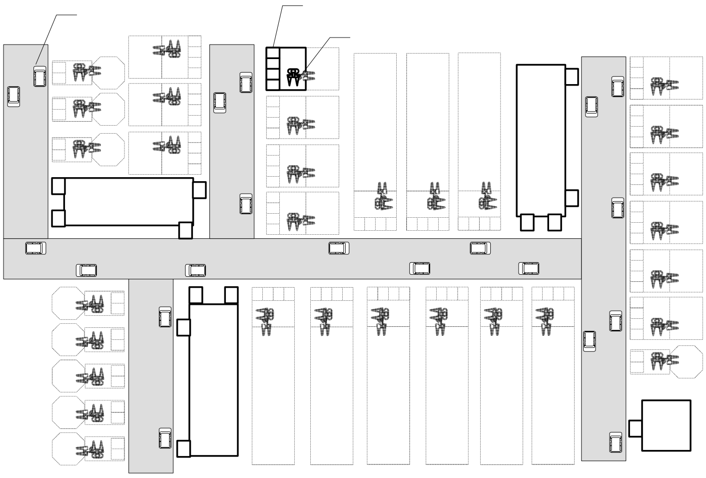


Figure 1: Layout of a LCD line with AGV systems

production stages, called the *front-end or fabrication stage* when combined, are performed in parallel. The front-end stage is considered more critical compared to the rest of the stages, since it includes very sensitive processing steps, such as photolithography, and it also requires a high class of particle-free environment. Most LCD manufacturers, therefore, have focused on throughput improvement in the front-end stage. In this paper, we also concentrate on the AMHS used in the front-end stage [3].

The layout for the front-end processing line typically follows a job shop configuration with corridors as shown in Figure 1. The job shop configuration is a layout in which similar processing machines are placed together and sections of a floor are distinguished by the function of machine groups. Note that the machines are lined up and face each other across the central corridor, which is called a *bay*. In each bay, a glass visits several machines to undergo all the required operations. Glasses are shipped to other bays by a machine that takes input from one bay and generates output to a different bay using other separated inter-bay transportation systems. In the bay, the transporter, such as AGV or RGV, serves as the material transport between machines. Typically, the transporter in the bay serves material movement only within the bay. For example, if AGVs are used in a bay, then most likely the AGVs works only on delivery requests within the bay, never leaving it. Some stockers are shown in the figure (marked as STK). These stockers temporarily store WIP (work in process). Note that some of the stockers are located between bays. That is, these bays are connected by the stockers. Glass movements between bays are done by the stocker robots inside of the stocker.

1.4 System Boundary

In our new design, we assume that the processing machine layouts are determined by LCD panel makers. This is a typical assumption in the industry because layouts are first given to AMHS solution providers by LCD panel makers. However, some flexibility is also given to AMHS designers, such as location of stockers or the amount of space allocated for the bays. Second, material movements are also given by LCD panel makers. Third, in our design, we focus on AMHS in a bay in the front-end LCD line. A typical example of the bay information provided by an

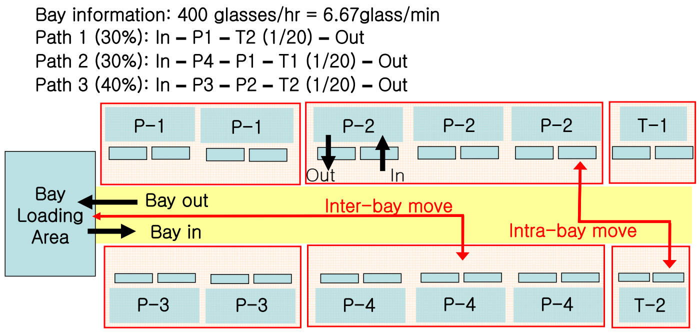


Figure 2: A bay information provided by a LCD panel maker

LCD panel maker is shown in Figure 2. In the figure, a typical machine space is allocated along the bay and material movements are also indicated. There are six different machine groups in the bay. Once a glass comes into the bay 30 percent of glasses take path 1, visiting a machine in the P1 group, and then move into T2, which is a sample tester. Note that when visiting T2, only one out of twenty glasses is sent and the rest of them leave the bay. The input or output locations for each machine and bay are also indicated in the figure. We focus on designing a hardware system that will be used in the bay.

2 NEW SYSTEM DESIGN

2.1 Customer Needs

In order to design an AMHS with a new concept, we first need to clearly identify the customers' (LCD panel manufacturers) requirements. The following list describes the main customer needs from AMHS:
1. Delivery rate – AMHS should meet the delivery rate and should not be a bottleneck in the production process.
2. Delivery time – AMHS should deliver a glass from one processing entity to another as soon as possible.
3. Glass protection – A glass delivered by AMHS should be handled carefully and any breakage or scratch on the surface of the glass is not acceptable.
4. Glass contamination – No particle should land on the surface of the glass and also AMHS should not generate any particles.
5. Reliability/maintenance – Since any failure in AMHS can cause a serious output reduction, AMHS should be robust and reliable.

2.2 Constraints and Functional Requirements

Then we come up with the following functional constraints and requirements:

Constraints:

- A glass can be handled on only one side of the two surfaces.
- The delivery rate of the system should be high enough to handle the material movement in the bays in the current manufacturing facility.
- The total footprint of AMHS should be less than that of the current system.
- The cost of AMHS should be less than that of the current system.
- The system should be reliable.
- The system should not be a source of particle contamination.

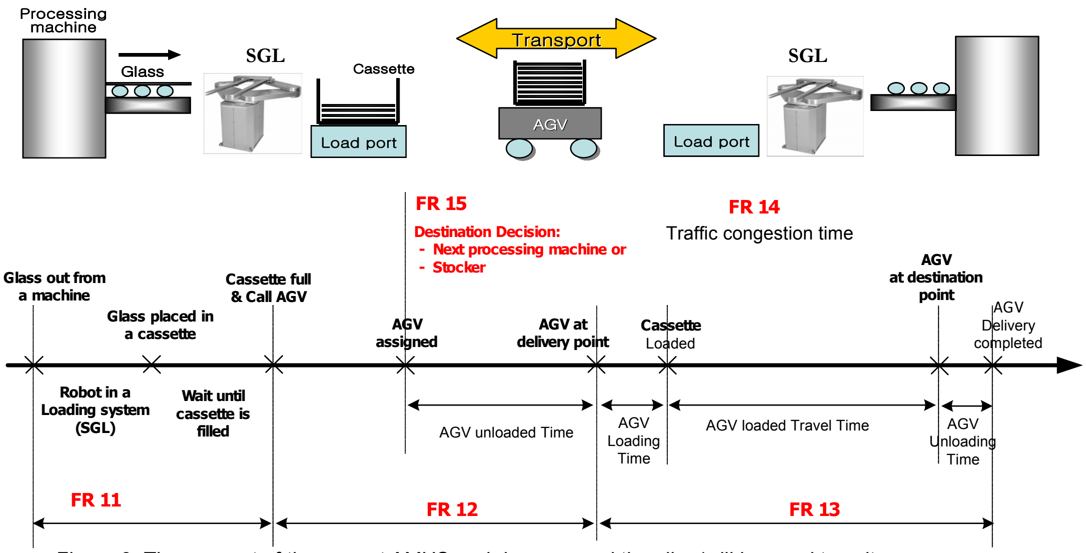


Figure 3: The concept of the current AMHS and decomposed time line(will be good to write

Functional Requirements:
FR1: Minimize the delivery time
FR2: Move glasses
FR3: Protect glasses from impact and particles

2.3 AXIOMATIC DESIGN ANALYSIS FOR AGV

The design analysis of the current system, particularly the AGV system, is conducted with AD. Figure 3 illustrates a basic concept of the AGV system. Once a glass is processed by a machine on the left, it needs to move onto the next step, which is performed by the processing machine shown on the right. When a processed glass comes out of the processing machine on the left, it is first stacked in a cassette by a single-glass-loading (SGL) robot. Then, if the cassette is filled with glasses, an AGV comes and picks up the cassette and then delivers it to the next processing machine. The cassettes are placed in one of the ports located in front of a machine. Due to the space limitation, the number of ports is limited to 2 to 4. Therefore, when the transporter tries to locate a port, it sometimes finds that all the ports are filled with cassettes and no port is available. If this happens (often called "cassette is blocked"), the transporter travels to a designated temporary storage place called a *stocker* and leaves the cassette in the stocker until the port is available. The design parameters corresponding to the FRs are:

DP1: Transport strategy (Number of AGVs, lot size, AGV dispatch rule, hardware parameters AGV speed, SGL capacity)
DP2: Transporter Type (AGV and SGL)
DP3: Storage Module (Cassette)

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \end{bmatrix} = \begin{bmatrix} X & X & X \\ X & X & X \\ 0 & X & X \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \end{bmatrix}$$

The design matrix indicates that the system is coupled. We discovered that the most critical as well as complex functional requirement is FR1, and therefore, our analysis in this paper focuses on analyzing FR1. The rest of the analysis on other FRs and decompositions can be found in [2].

The delivery time can be decomposed as shown in Figure 3. The decomposed FRs with the related time parameters are described below.
FR11: Minimize the lot completion time. (*Tgl*: Lot completion time)
FR12: Minimize the queue waiting time (*Tq*: Waiting time until AGV comes to the requested load port)
FR13: Minimize the non-congested travel time (*To*: Travel time)
FR14: Minimize the traffic congestion time (*Tc*: Traffic congestion time)
FR15: Minimize the number of stocker visits due to blockage (*Pb*: Probability of the blockage)

The corresponding design parameters are:
DP11: Production rate of the processing machine (*r[glasses/min]*) and glass handling time of the SGL (*Tg*)
DP12: Number of AGVs in the bay (*N*)
DP13: Average speed of AGV (*V*), and cassette loading/unloading time (*Tcl*)
DP14: Transfer lot size (*L*)
DP15: Number of ports in a loading area (*Np*)

In FR11, *Tgl* is interpreted as waiting time in a cassette due to the fixed lot size (*L*). For example, if a *i* th glass in a lot just finished from a process. As soon as it comes out from a machine, which processes a glass at the rate of *r*, it will be transported into a cassette by the single-glass-loader (SGL). Since it is the *i*th glass, this glass has to wait until the rest of glasses fill the cassette. This waiting time is $(L-i)(1/r)$. Inversely, if glasses in a cassette are to be loaded into a machine, waiting time until the *i*th glass is handled by SGL is $i(1/r)$. The combined these two waiting time, $(L-i)(1/r) + i(1/r) = L/r$, is the waiting time in the cassette *Tgl*.

$$Tgl = \frac{L}{r} \qquad (1)$$

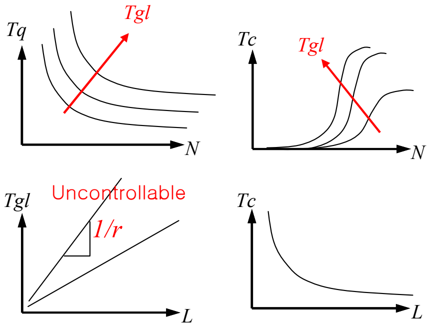


Figure 4: Conflicting design parameters

The handling time of an SGL, *Tg*, is usually around 10 seconds. Since the rate at which an SGL handles a glass should be higher than the processing rate, the following constraint is stated:

$$Tg < \frac{1}{r} \qquad (2)$$

The cassette size is fixed and a widely used cassette size is around 30 glasses. Since an AGV delivers only one cassette at each delivery job, we can assume that the size of cassette is the transport lot size.

Next, FR12 is minimizing the queue waiting time – the amount of time until an available AGV arrives at the requested port. This waiting time is directly related with the number of AGVs in the bay. Intuitively, if there are many AGVs in the bay, the queue waiting time will be decreased and vice versa. Consequently, designers try to add more AGVs to reduce the queue waiting time in the bay. There are other parameters that also impact the queue waiting time, such as the frequency of sending the delivery request to an AGV, speed of AGVs, and distance between the requested loading system and the location of the AGV which is dispatched to the loading system. Using the multi-server Queueing Theory [3], we can approximate the equation for the queue waiting time as the following:

$$Tq \cong \left(\frac{Db}{v \cdot N}\right) \Big/ \left(1 - \frac{v}{Db} \cdot \frac{r}{L}\right), \qquad (3)$$

where *Db* is the average distance in a bay.

FR13 is minimizing the AGV travel time with a loaded cassette, *To*. This quantity *To* includes the cassette loading/unloading time, *Tcl*, but excludes any time delay caused by traffic congestion. Then the *To* can be stated as,

$$To = \frac{D(i,j)}{v} + 2 \cdot Tcl, \qquad (4)$$

where *D(i,j)* is the distance form the loading system *i* to *j*.

FR14 is minimizing the travel congestion time, *Tc*. Since the space for AGVs in a bay is limited, the only possible solution to reduce the traffic congestion is to minimize the number of delivery requests by using a large transport lot size. That is, if the transportation lot size gets bigger, fewer trips are required. The congestion time is approximated such that,

$$Tc \cong (1 - u^{N-1}) \frac{(Tcl)^2}{2} \Phi(i,j) \frac{r}{L}, \qquad (5)$$

where *u* is an average utilization rate of an AGV and $\Phi(i,j)$ is a traffic factor from a loading system *i*, to *j*. The detailed derivation and analysis of the traffic congestion is described in [4]. In the equation†, the traffic congestion increases with the number of vehicles, *N*, while it decreases with the lot size, *L*.

The last functional requirement, FR15, is minimizing the number of additional trips to the stocker. It is often observed that an AGV loaded with a cassette cannot find an available port in the loading system because all the ports are filled with other cassettes. In this case, the AGV moves to a stocker in the bay, instead of the destination loading system, and unloads the cassette in the stocker system. The cassette is temporarily held in the stocker until a port in the loading system is available. This re-routing of the cassette due to the port unavailability is called *blockage*. The event of blockage requires more AGV travels, causing extra traffic and eventually increasing the delivery time. The number of ports, *Np*, is a primary parameter in the probability of the blockage, *Pb*. Intuitively, if there was an infinite number of ports in a loading system, there would not be any blockage. Therefore, AMHS designers add as many ports as possible to reduce the probability of the blockage. However, the probability of the blockage is also dependent on other parameters, including *r, L, v,* and *N*. It is not straightforward to derive a closed form equation for *Pb* and it is outside of the scope of this paper. We simply state that

$$Pb = F(Np, v, N, \frac{r}{L}) \qquad (6)$$

The detailed analysis of the function is described in [4].
From the equations (1) to (6), we can construct the following design matrix:

$$\begin{bmatrix} FR11 \\ FR12 \\ FR13 \\ FR14 \\ FR15 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & X & 0 \\ 0 & X & 0 & X & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & X & 0 & X & 0 \\ X & X & X & X & X \end{bmatrix} \begin{bmatrix} DP11 \\ DP12 \\ DP13 \\ DP14 \\ DP15 \end{bmatrix} \qquad (7)$$

This design matrix indicates that the system is a coupled design. The coupling involves direct conflict between parameters. For example, increasing DP12, the number of AGVs (*N*), will reduce the queue waiting time (*Tq*); however, it also increases the traffic congestion time (*Tc*) – a conflict between FR12 and FR14 with the same DP12. Another conflict is between FR11 and FR 14. Suppose that the designers use a smaller lot size, *L*, to reduce the time in the loading system, *Tgl*. The smaller lot size will require more frequent delivery requests and eventually increase the congestion traffic, *Tc*. These conflicting events are shown in Figure 4. Another, and worse problem with the current design is that the performance of the system highly depends on an uncontrollable parameter, which is the processing rate of the machine, *r*. Note that the machines in LCD production lines, particularly in the front-end processes, are highly unpredictable

† Note that the vehicle utilization *u* is also a function of *Tc*. Therefore the function has the form of *x=f(x)*. It is proven that the solution can be evaluated by an iterative method and it always converges within a few iterations.

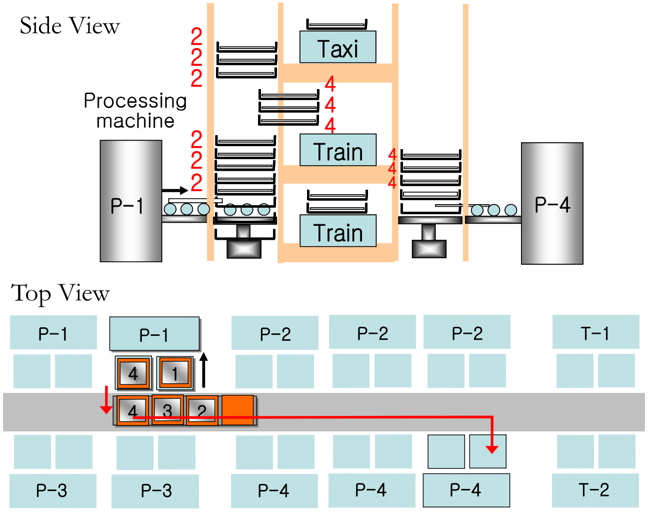


Figure 5: New system delivery concept

due to various reasons: unexpected machine failures, unreliable machine repair times, and frequent machine stoppages due to setup changes. That is why the quantity *r* is treated as a random variable with a high variation. The direct impact of this unpredictable parameter goes to FR11 – minimizing the time in the loading system. As shown in Figure 4, if *r* gets smaller – the production rate goes down – the sensitivity of *Tgl* to *L* becomes bigger, reducing the robustness of the system. The impact of the uncontrollable parameter is not limited to FR11. The increased *Tgl,* due to *r,* also augments the probability of blockage. If a port is blocked, then AGVs have to be re-routed to the stocker with the loaded cassette, causing the higher utilization of AGVs and resulting in extra traffic in the bay. Therefore, the increased *r* eventually increases the traffic congestion time, *Tc*, and the queue waiting time, *Tq*, as shown in Figure 4. The impact of *r* is also captured with the equations in (3) and (5).

Notice that in Equations (1), (3), (5), and (6), *Tgl, Tq, Tc*, and *Pb* are functions of L/r. That is, all the influence of *r* is through the size of *L*. In other words, DP14 (*L*), the design parameter that impacts almost all the FRs, is tied up with the uncontrollable parameter, *r*. The tight bonding of *r* and *L* is created because loading stations are initiating AGV moves and they request AGV at the rate of r/L. Therefore, it is clear that in order to improve the system, we need to break the bonding between *r* and *L* and then decouple the influence of *L* on the FRs. However, many engineers in the production lines using the AGV system try to solve the problem by searching for optimal parameters. Such an optimization approach could not solve the problem due to the system complexity, i.e., the coupling of FRsand the influence of the uncontrollable parameter *r*. Other problems associated with the rest of the FRs are:
1. The system requires precision mechanism in the SGL.
2. The cost of AGVs and SGLs is too high.
3. AGVs require significant space in the production lines.
4. Large buffer space needs mean that a stocker system is required.

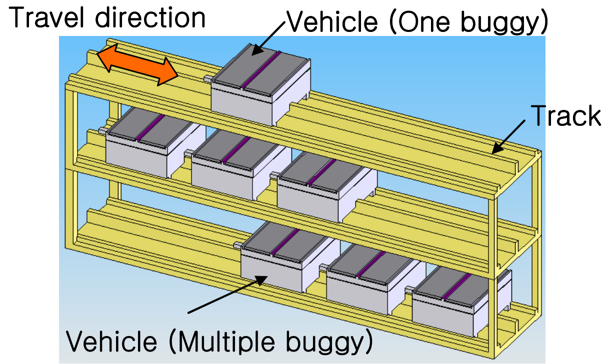


Figure 6: Multiple-layer track

3 NEW DELIVERY CONCEPT DESIGN

The current system analysis with AD has clearly indicated to the target areas we need to focus on in designing a new system:
1. Guarantee the independence of FRs.
2. Decouple the DPs.
3. Increase the robustness.
4. Reduce operational complexity by using functional periodicity to determine the system parameters instead of using optimization.

3.1 FLEXIBLE LOT SIZE

First, we need to break the strong operational bond between *L* and *r* to make the new system more robust. We have concluded that the root cause of this bond is the fixed size of the transfer lot *L*. Therefore, instead of using the fixed transportation lot size, a stackable single-glass tray is used, adding flexibility in the lot size. This flexible transportation lot concept eventually eliminates the influence of the randomness of the production. With the flexible lot sizing, the delivery move does not need to be initiated by a loading station, making the system robust to the unpredictable production rate.

3.2 NEW TRANSPORTER

Next, we need to achieve the independence of FR12 (minimizing the queue waiting time) and FR14 (minimizing the traffic congestion). Intuitively, if the traffic density is reduced by providing a large space, the independence could be easily achieved. However, this is not an option due to the space constraint. Instead, we provided extra space by designing a multiple-layer track system, as shown in Figure 5. Also, we allowed only one vehicle per bi-directional track. The number of tracks depends on the traffic capacity. In this design, since there is only one vehicle running on a track, no traffic congestion is present and the queue waiting time is independent of the traffic congestion. The queue waiting depends only on the number of tracks (layers) and operational rules of the vehicle. In order to meet the delivery capacity, the design is formulated such that the vehicle can have multiple buggies, such as a train.

3.3 BUFFER STATION

The new design of the system is illustrated in Figure 6‡. In the figure, there are three layers on tracks installed in the bay. Once a

‡ Detailed descriptions of the system and motion control are explained in [2].

glass comes out of the processing machine, it is first handled by a roller transporter and inserted into a single glass tray. The total amount of this operation – glass handling time – is denoted by *Tsg*. Then the tray is stacked from the bottom and waits for a vehicle in the buffer station, which will replace the current loading station. In the buffer station, as shown in Figure 7, there are two separate buffering areas: input stacking and output stacking areas. Once a buffer station receives glass-loaded trays from a vehicle, it stacks the trays in the input stacking area and starts feeding a glass into the machine from each tray. The emptied tray is moved to the output stacking area and waits until the finished glass comes out of the machine. When a glass comes out, it is inserted back to a tray and waits for a vehicle for transportation to the next destination. This buffer station is capable of loading and unloading multiple trays from a vehicle in one loading/unloading motion, which is an essential requirement to achieve the functional periodicity to be discussed in the last section. Also note that the buffer station can move vertically up and down two access all layers of triple-deck transportation system in Figure 7.

Operation of this buffer station is illustrated in Figure 6. In the bay, a material path (Path 1) needs glasses to visit P1 and move to P2, while the other material path (Path 2) requires P1 followed by P4 (note that there are several different flow paths in a bay). Therefore, the next destination of the glasses placed in the output buffer station of P1 is either P2 or P4. In the figure, the number next to the tray indicates its destination machine. Due to the group travel property, the glasses with the same destination are stacked next to each other. The buffer station is designed such that when it needs to load a set of trays to a vehicle, it can load multiple trays that are placed in any part of the stack. Figure 6 illustrates that the vehicle in the middle track loads the trays that need to go to P4. The operation sequence of buffer station is shown in Figure 8§.

4 SYSTEM ANALYSIS

4.1 OPERATION POLICY

A set of rules describing scheduling and assignments of vehicles is defined as an *operation policy*. Our primary goal is to design new AMHS hardware. However, we suggest one possible operation policy to show that the new design also provides various options and flexibilities for operations. In the current AGV system, an AGV responds to a delivery request initiated by a loading system. That is, the loading system has an active control over the AGV. This is similar to the taxi system in that a passenger calls a taxi whenever service is needed. On the other hand, a train system circulates on a predefined route and picks up passengers waiting at stations. The passengers do not have control over the bus or train. Intuitively, if traffic density is low, the taxi system tends to transport a passenger faster. However, if there are too many taxis servicing an area, causing heavy traffic congestion, the passengers in the area might be better off by taking trains or subways.

§ Detailed descriptions of the system and motion controls are explained in [2]

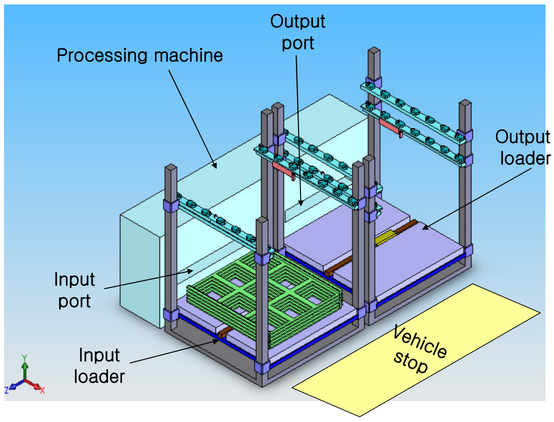


Figure 7: New loading system operations

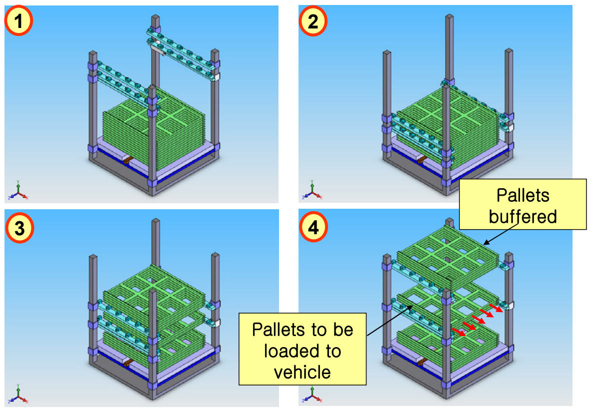


Figure 8: New loading system operation sequence

In the current fixed lot size system, the taxi system has been the only option due to the large cassette size and weight. If a vehicle transports more than two cassettes, the vehicle requires a significant amount of loading space and power. That is why the AGV system uses one cassette as a transportation lot size. However, with the new design, a single glass can be handled individually, making the transportation lot size flexible. Usually, when glasses on the order of a hundred come to a bay in an hour, heavy material flow is observed.

Therefore, our operation suggestion is to use a train/taxi hybrid system. To clarify, the term vehicle refers to a transporting system unit that includes the train or taxi. The train is a vehicle traveling on a predefined route and usually consists of multiple buggies, while the taxi is a vehicle that serves upon request and normally consists of one buggy. The operation policy is the following:
- Three layers of tracks are installed as shown in Figure 6.
- The bottom layer has a track with a train (multiple buggies) transporting glasses in and out of the bay – the inter-train.
- The track in the middle has a train transporting glasses moving within the bay – the intra-train (we assume that loading/unloading for glasses coming in and out a bay is done in a *bay loading area* located right next to each bay. In the area, glasses entering to the bay are loaded onto the inter-train, while glasses

leaving the bay are unloaded. Thus, the inter-train never moves to another bay. The glass moves between bays are done with another transporter that the current project can be extended to include.
- The top track has a taxi (one buggy) that moves a glass requiring a visit to testing machines in the bay. For example, in Figure 2, only one out of twenty glasses visits T1 and T2.
- Since there is only one bi-directional track per vehicle, the train and taxi move back and forth to do the delivery job.
- The trains stop at all the machines to load and unload the trays.
- The taxi moves only when there is a delivery job.

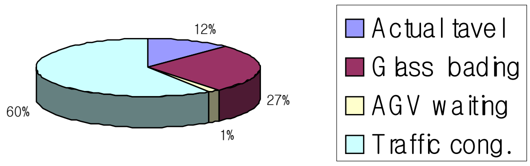
The main glass movements are done with trains. However, we added a taxi because it is not efficient that the trains visit the machines with a low demand on every trip. The delivery request from these machines can be covered more efficiently with the taxi. Moreover, the taxi also can be utilized as a backup system when there is a failure in a train. The bottom train is used for the inter-bay movements. Since this train will be the busiest vehicle and also makes the longest trips, it may cause turbulent flow. By placing the cause of the turbulence at the bottom, we can reduce the risk of particle contamination. For the same reason, the taxi is placed on the top track since it is the least busy vehicle. This idea is derived using decoupling based in AD Theory.

4.2 AD ANALYSIS FOR THE NEW SYSTEM

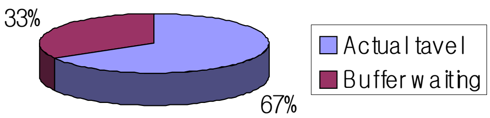
Since the new system replaces the loading system with the buffer system and uses a single glass tray instead of a cassette, some modifications in the FRs are needed. However, the basic concept of the delivery time decomposition is still the same. New FRs are:
FR11: Minimize the time to handle a glass in and out of a tray (*Tsg*: Time to handle a glass in and out of a tray)
FR12: Minimize the queue waiting time (*Tq*: Waiting time until a vehicle comes to the requested load port)
FR13: Minimize the non-congested travel time (*To*: Travel time)
FR14: Minimize the traffic congestion time (*Tc*: Traffic congestion time)
FR15: Minimize the number of stocker visits due to blockage (*Pb*: Probability of the blockage)

The corresponding design parameters for the new system are:
DP11: Production rate of the processing machine (*r [glasses/min]*), and the angular velocity (*Va*) and diameter of the roller (*d*) in the buffer station.
DP12: Operation policy of the vehicle.
DP13: A vehicle speed (*V*), and cassette loading/unloading time (*Tcl*).
DP14: One vehicle per track system
DP15: Tray holding capacity of the buffer station.
In FR11, *Tsg* is measured from the moment that a glass comes out of the processing machine to the instant that a glass is inserted to a tray. The glass is moved by friction force between the bottom surface of a glass and the surface of rollers in the buffer station. Let us denote *Lg* to be the length of a glass then *Tsg* has to satisfy the following constraint:

$$Tsg = \frac{Lg}{\frac{d}{2} \cdot Va} < \frac{1}{r} \qquad (8)$$



AGV system: mean = 366sec



New system: mean = 67sec

Figure 9: Simulation results – Time distribution

For FR12, waiting time, *Tq*, depends on the operation policy. For instance, if we use the operation policy suggested in the previous section (inter-train, intra-train, and taxi system) and the inter-train stops at each processing machine in the sequence of P1-P2-P4-P3 in Figure 2, with the total circulation time of *Ti*, then the waiting time for the train will be uniformly distributed between 0 and *Ti* with a mean of *Ti/2*. The travel time of a glass is mainly governed by the vehicle speed and the loading/unloading time. However, it is also influenced by the operation policy. For example, if we use the same policy above with the circulating intra-train moves, then the travel time for a glass traveling from P1 to P2 is far less than the travel from P1 to P3. For FR15, we believe that as long as the buffer station provides enough stacking capacity, then an additional trip to a stocker is not necessary due to the flexible lot size that enables lesser WIP in the bay. Note that in the AGV system, each loading system normally has two loading ports. If two transportation lots are occupied in the port, any incoming lot is blocked. However, if we use a smaller lot size, and ensure that the buffer station can stack at least 50 trays, it is not likely that the buffer will be full in normal operation, so no blockage will occur. We can construct the following design matrix:

$$\begin{bmatrix} FR11 \\ FR12 \\ FR13 \\ FR14 \\ FR15 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP11 \\ DP12 \\ DP13 \\ DP14 \\ DP15 \end{bmatrix} \qquad (9)$$

The design matrix is a slightly decoupled design but the all the strong coupling that was presented with the AGV system is eliminated. Note that the other design parameters such as the number of buggies and the number of layers are not the design parameters that satisfy this particular FR. However, these parameters directly influence some of the constraints, such as cost and delivery rate. That is, as long as these parameters meet the constraint, particularly delivery rate, the system guarantees the decoupled design matrix. The next section examines if the new design meets the delivery requirements.

4.3 SYSTEM VERIFICATION AND INFORMATION AXIOM

With an actual data set for a bay provided by one of the LCD panel makers, we ran simulations for the system operating with the suggested policy. We used four buggies for each train. We used the average travel speed of the vehicles as 10 m/sec and the loading/unloading time of the vehicles as 10 sec. The simulation results proved that the system meets the delivery rate. In addition, the delivery time is far less than the AGV system as shown in Figure 9. In the AGV system, ten AGVs were used in the bay to meet the delivery request rate. However, such a large number of AGVs in the limited area also created a considerable amount of traffic congestion. As indicated in the graph, around 60 percent of the delivery time is caused by the traffic congestion. Moreover, 27 percent of the time is consumed by the glass waiting until the cassette gets filled (glass loading). On the other hand, in the new system, no congestion time delay is present due to the one vehicle one tack configuration. Moreover, there is no time delay caused by the glass filling in a cassette. Only 33 percent of the total delivery time is used in waiting for the service in the buffer system and the rest of the time is used for the transportation time. Figure 10 compares the two results on the same scale. According to the Information Axiom, the design that has the highest probability of achieving the FRs is the best design. Although the rest of the FR2 (deliver glasses) and FR3 (protect glasses) might be difficult to measure at this conceptual stage, FR1 can be easily quantified. Therefore, if we compare the total delivery time of the two systems, we can easily find that the new design superior to the currently used design, based on the Information Axiom. The new system not only considerably reduces the delivery time, but also has less variation in the delivery time. This result proves that the new system provides a more predictable solution. Finally, we have also accomplished decoupling at the highest level of FRs with the new design. The detailed design analysis is shown in [2].

4.4 Functional Periodicity

The introduction of periodicity in a system reduces complexity of operation, gives ability to reinitialize the system, and maximizes efficiency [5]. In our new design, cyclically repeating motions of the train vehicle are translated to functional periodicity to maximize the performance of the system. In the operation policy described in a previous section, the inter-train vehicle transports glasses going in and out of the bay. In the bay loading area, all glasses entering the bay are loaded on the empty vehicle. Then the vehicle circulates through the bay. In each station, glass to be processed is unloaded and then any glass that has undergone a process and needs to leave the bay is loaded onto the vehicle. After one complete circulation, the vehicle comes back to the bay loading area and discharges all glasses that have been loaded in the bay. At this moment, the system re-initialization occurs. Total travel time for vehicle to circulate a bay is Ti. Although the functional periodicity is an effective way of reducing complexity, it might not be easy to reinitialize the system in a deterministic manner. For example, the inter-train vehicle will not stop at a particular machine if the vehicle does not have a glass going to the machine and there is no glass that has been waiting for the vehicle. Therefore, Ti, the period of re-initialization, is considered a random variable. Then the waiting time of a glass, Tq, in the bay area is also a random variable and its expected value is derived in [2]. The result is expressed as follows

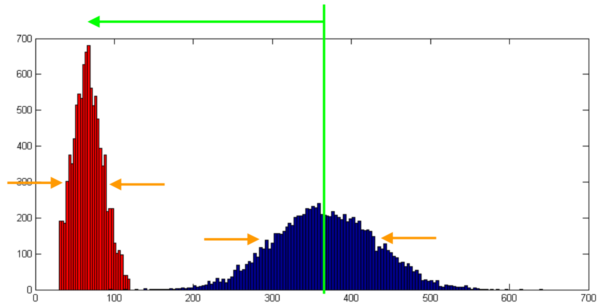


Figure 10: Information Axiom and the new system

$$E[Tq] = \frac{Var[Ti] + E^2[Ti]}{2E[Ti]} \qquad (10)$$

That is, if Ti is a deterministic variable – the vehicle always comes as scheduled – $Var(Ti)$ will be zero and the waiting time is $Ti/2$, which is the minimum value of $E[Tq]$. As the variation gets bigger, the expected waiting time increases. This analysis suggests the following interesting policy: A vehicle should stop at every station. If it stops at a station where no glass needs to get on or off the vehicle, the vehicle should be idle for the length of loading time. In this way, we can reduce the variability of Ti, achieving a smaller expected value of Tq. There are other various ways of analyzing and constructing an operation policy using the functional periodicity, which might be the right area to focus on as our next project topic.

5 CONCLUSIONS

We have presented the design procedures and analysis of a new AMHS for LCD production lines using AD Theory. We systematically identified the problems of the current system and logically tracked down the root cause of these problems by decomposing the current system. Then we redesigned the system with the design axioms described in AD. We showed that the new system is decoupled and robust. The simulation results proved that the performance of the new system is remarkably improved compared to that of the current system. We also briefly introduced how the operation policy of the new system can be improved by incorporating the functional periodicity.

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