Evaluating factory performance of photovoltaic manufacturing lines by using log data

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ABSTRACT

Investments in large photovoltaic factories can lead to high capital expenditure. To achieve a fast return on investment, it is essential to ensure a high utilization of process equipment. Optimization of photovoltaic factory performance requires a fundamental understanding of the processes as well as of the material flow and manufacturing equipment. Fraunhofer IPA has developed an approach to gather and analyze the factory data in order to detect and understand the logistic influencing factors. With this factory data, the performance of material flow systems and production equipments can be evaluated, leading to detection and elimination of inefficiencies in the manufacturing lines. The methods of acquiring and analyzing factory performance data as outlined in this article mainly focus on thin-film manufacturing lines, but are also applicable to crystalline technologies.

Introduction

Material flow systems are becoming more and more important in the photovoltaic industry. Factory capacities and their throughput increases, as well as modern factories, have a high degree of automation. An optimized logistics planning and operation of the factories is therefore crucial to the economic success of the factory. Similar to almost all other manufacturing industries, the material flow system has comparably low investment and running costs. A good planning and optimization of the system is mandatory to avoid production losses caused by lack of material. Furthermore, valuable performance data is needed to achieve good planning and further optimization.

Material flow systems

A high degree of automation in material handling and transportation is implemented in current thin-film factories. The different handling systems are controlled by a supervising software system that controls the flow of the material throughout the factory. Due to there being potentially several different hardware suppliers of the material handling systems and the lack of a standardized equipment interface, this task is challenging in terms of data collection and data management. The situation becomes even more complex in the case of a combination of batch and single substrate handling, as tracking of each substrate produces a huge amount of data, if properly implemented. Using appropriate tools, this data can be used to evaluate the performance of logistic systems.

The predominant task of a transport system is the on-time delivery of lots or single substrates within the factory. The importance of the task is especially pertinent for bottleneck processes as unnecessary idle times lead to expensive unused capacity. To evaluate the performance of transport systems, different indicators can be analyzed:

- Utilization, which shows the capability of a transport system to react to different workloads.
- Delivery time – the time needed to accomplish a transport task.
- Waiting time, or the period of time in which material is waiting to be transported after a finished process.

The schematic in Figure 1 exemplarily shows time segments and time stamps that are recorded while substrate handling occurs throughout the batch transportation area of a factory. The time sequences of an automated lot transport task from equipment A to equipment B is clearly portrayed. (We use the term "vehicle", but other transport methods can also be used.)

Time segment 1: A lot is finished at a process and ready to be picked up. The time until a vehicle arrives at the load port (referred to here as t_1).

Time segment 2: The time needed to load the lot onto the vehicle (referred to as t_2).

Time segment 3 & 6: The time taken for the vehicle to arrive at the destination load port (referred to as $t_{3,6}$).

Time segment 7: The time needed to unload the lot, or set-down time (referred to as t_7).

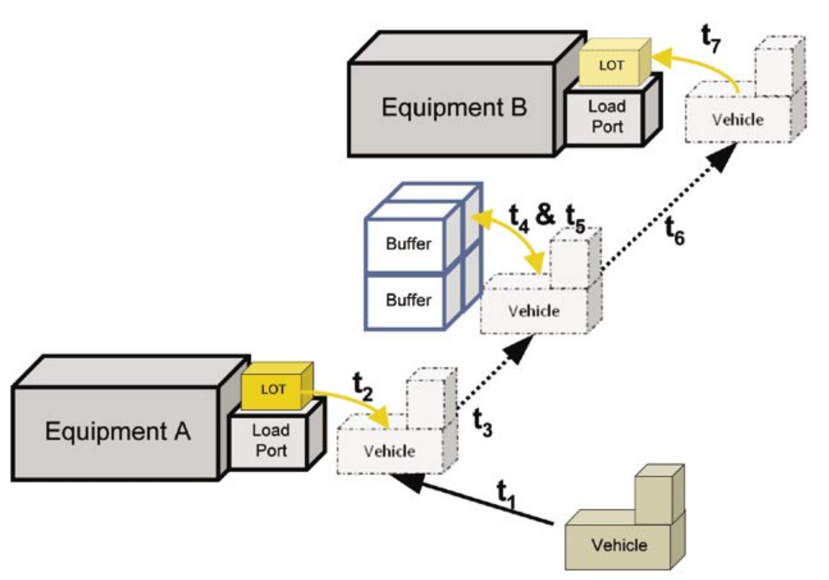

Figure 1. Time segments of an AGV-based lot transport.

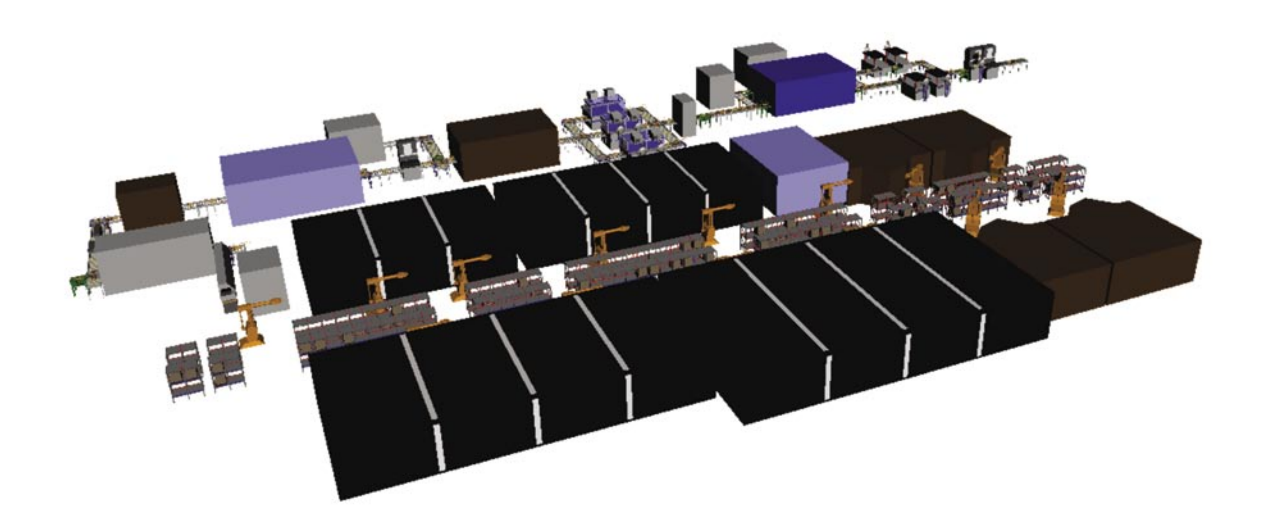

Figure 2. Example layout of a manufacturing line.

Timestamp	Event	EquipSection	LotID	CassetteID
14.02.2007 06:03:59	Substrate Entered	Fab In	1	22
14.02.2007 06:04:20	Location Changed	Rack Out	1	22
14.02.2007 06:04:45	Location Changed	Rack In	1	22
14.02.2007 06:06:02	Substrate Entered	Process In	1	22
14.02.2007 06:07:38	Substrate Entered	Fab In	2	85
14.02.2007 06:08:04	Location Changed	Rack Out	2	85
14.02.2007 06:10:38	Substrate Removed	Process Out	1	22
14.02.2007 06:10:53	Location Changed	Rack Out	1	22
14.02.2007 06:12:14	Location Changed	Rack In	2	85
14.02.2007 06:12:16	Substrate Removed	Fab Out	1	22
14.02.2007 06:13:49	Substrate Entered	Process In	2	85

Table 1. Simplified example of a log file of logistical performance data.

The main indicator delivery time is defined as $t_{delivery} = t_1 + t_2 + t_{3,6} + t_7$

In the case of a lot needing to be buffered before it is transported to its destination process, the overall calculation changes. A transport task would then go from equipment A to a buffer as destination, and the subsequent transport from this buffer to equipment B.

Figure 2 shows a factory layout where the performance of the transport system can be evaluated by using the approach described in the following section.

Acquiring factory performance data

During the last few years, great progress has been made in measuring and improving the performance of cells and modules. The photovoltaic industry was (and to an extent still is) driven by technology aimed at improving the product. This is due to the small time span (relative to mature industries) of production of several photovoltaic products and processes. On the brink of mass manufacturing, this situation is going to change. Already, operators of factories do not only focus on high product quality, but also on achieving a stable and high factory output.

The situation in many factories today is characterized by a fluctuating level of module performance, even for products of the same production batch. This holds especially true for the thin-film branch of photovoltaics. The peak power of the modules often differs by several watts. Factory owners would prefer a stable output rather than the fluctuation of modules with a very high performance and modules with low performance, as it would facilitate a systematic investigation for the reasons of low module performance as well as a reliable volume which can be put on the market.

At the same time, factory owners are focusing more and more on factory output, which, in terms of cells or modules, depends on the following parameters:

- Yield (amount of modules meeting the quality requirements)
- Scheduled maintenance activities of equipment
- Unscheduled repair activities of equipment
- Lack of material and other circumstances causing equipment stand-by time

All these factors have a huge impact on the output of the factory. Therefore, it would be beneficial if there were ways of measuring these parameters in order to carry out reliable analysis. Unfortunately, this data is often not available or the reliability of the data is deemed too low. The main reasons for this are the lack of sophisticated MES (Manufacturing Execution System) in the factories as well as missing standardized interfaces for linking manufacturing equipments to the MES.

Reliable data such as this would be highly beneficial, especially in the operation of large factories. Future factory control systems will not only deliver accurate data from measurements and process parameters, but also data about factory performance in terms of logistical throughput.

Data for measuring logistical performance is partly available from running factories, and this paper will illustrate the usage of this data in the following sections. The data shown in Table 1 originated from a production process in which substrates are transported in cassettes and also partially processed in batches.

The data is structured in a log-file format. Specific pre-defined events are recorded and stored, typically in a text file. In the case of logistical performance measurement, the events are triggered if a substrate or a carrier (cassette) is moved from one defined location to another (e.g. from a conveyor belt into a process equipment). This procedure requires the tracking of substrates or carriers, which might not be the case in inline wafer manufacturing lines.

Typical data sets usually contain more information, but the reduced complexity shown in Table 1 illustrates the structure of the data more clearly. The main columns of the example are:

Timestamp

Every recorded event is equipped with a timestamp of the occurrence of the event. Timestamps usually include date (day, month and year) and time (hour, minute and second).

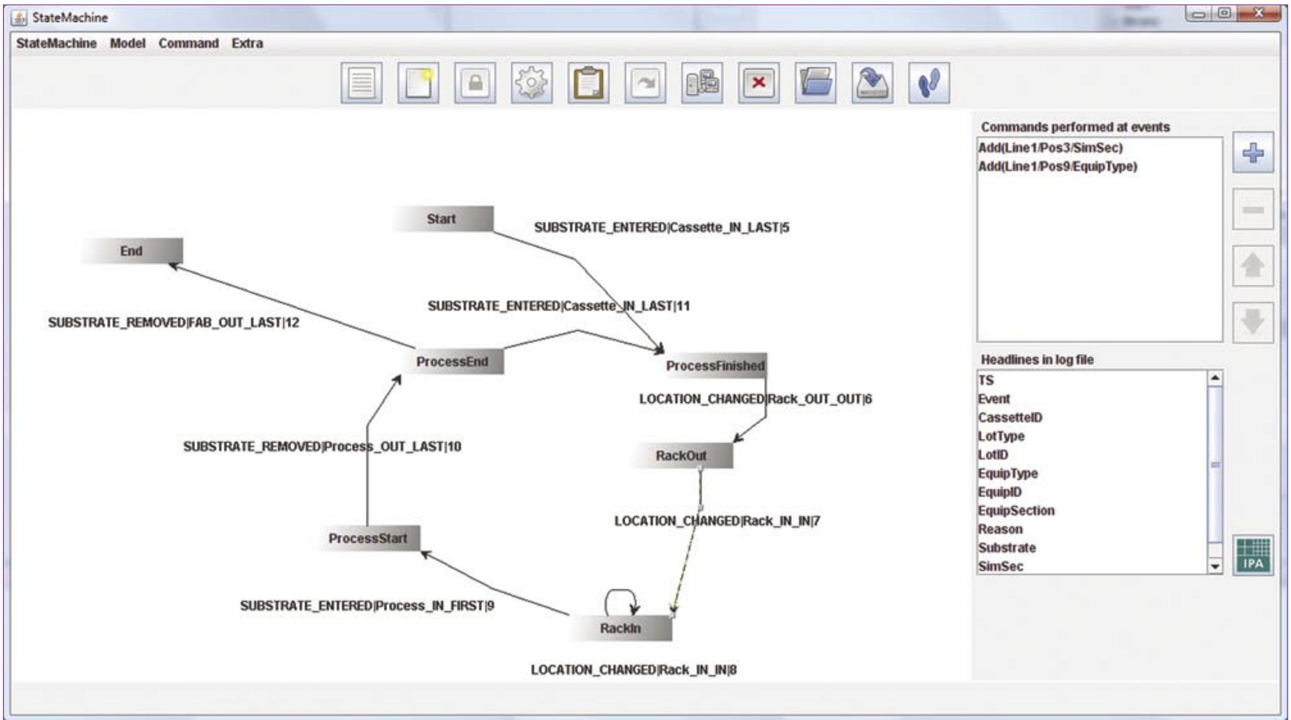

Figure 3. Example state model in Fraunhofer IPA state machine tool.

Event

An event designates the activity that has been carried out with a substrate. An event can also be enhanced with optional sub-events to further specify the activity.

Identification

Identification is effected via identification numbers. Lots have an identification number, as do containers, also called cassettes. Shelves, which serve as racks, often also feature a distinct identification number.

Typical further data fields in the log file are equipment-ID, equipment section, substrate or lot type, cassette-ID and sub-events. Further sources of logistical performance data are simulation models, which are used to plan and optimize photovoltaic manufacturing lines and factories. The described method of acquiring performance data has several advantages. One would be the simplicity of the data as the structure is well defined and can be implemented in almost every type of control system. Although the structure itself is simple, a broad spectrum of different analyses can be obtained from the data. Therefore, almost every needed logistical analysis is based on the same data set.

Using finite automat

The idea behind the analysis is the sequential run through the log file, which is sorted by the timestamp. An object (e.g. a lot) is defined as a tracking item. A separate object is created for each such tracking item to allow each item to be tracked individually. The procedure now foresees that a tracking item can be situated in different states. The state changes if a pre-defined event occurs in the log file. By changing a state, a definable activity can be carried out. In our case, this is usually the creation of a tracking item and the gathering of information out of the log file. The concept behind this approach is called a finite automat.

A finite automat M is specified using a 5-tuple $M = (Z, \Sigma, \delta, z_0, E)$. It consists of five components:

- Z is a finite amount of states
- Σ is the so-called input alphabet
- $\delta: Z \times \Sigma \rightarrow Z$ is the transient function
- $z_0 \in Z$ is the start state
- $E \subseteq Z$ is the amount of end states.

A finite automat is moreover called deterministic if at one state, the following state is clearly defined by a certain character input. Finite automats can be illustrated by means of directive, labelled graphs. The states are mainly demonstrated through use of nodes, whereas the transition from one state to the next is represented by arrows. We refer to such a model as a state machine.

Finite automats are now used to build graph models of different chains of transport moves that can occur in a factory. A simplified example of such a graph is depicted in Figure 3. The model is described by three entities.

States

Material can be situated in different states. For instance, a lot can be in a state of waiting on a load port to be picked up by a vehicle (as shown in Figure 1). For each lot that is created, a start state is defined. The end state is reached as soon as the lot has arrived at the defined terminal stage (e.g., removal from the manufacturing line or reaching a specific process) and is no longer considered part of this analysis.

Events

The events constitute the input alphabet of the finite automat. An event occurs if, for example, a lot is transferred from the load port onto a vehicle.

Transitions

The transient function is defined as the shifting of an entity from one state to another caused by an event.

To evaluate the performance of the transport system, the log files of real MES/MCS factory data or from simulation models have to be analyzed. All valid states of the tracking item have to be defined, as shown in Figure 3. Additionally, all transitions that can occur need to be noted in combination with the events that are triggered by them ("Location changed|Rack_OUT" in the example). Finally, the entity type that is to be tracked can be chosen. Depending on the purpose of the analysis, this could be a number of entities ("LotID"; "ContainerID"; "SubstrateID"), depending on the purpose of the analysis. This information is sufficient to create the finite state model and perform evaluations using the Fraunhofer IPA state machine tool. This tool also provides the possibility of automatically analyzing the log file and listing all of the available discrete events for modeling.

Using this model, the state machine can be configured to parse the log files and extract and process the data according to the needs of the user. Therefore, "commands" can be defined, which allow the customization of the result file generated by the tool. This typically incorporates timestamps, locations or the change of the tracking entity (e.g. from SubstrateID to ContainerID).

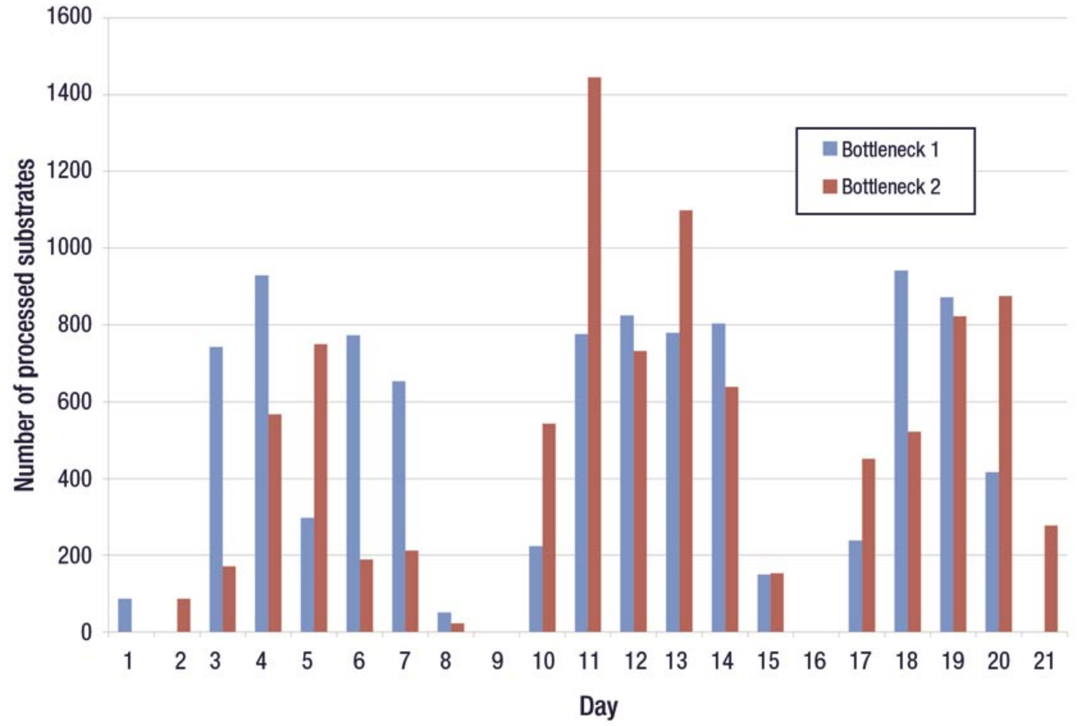

Figure 4. Analysis of the throughput of two bottleneck processes.

Results

The described procedure is currently used to benchmark results from simulation models as well as to analyze the factory behaviour.

An example log file has been used to analyze factory behaviour during ramp-up. The timeframe of the analysis was set to three weeks, whereas longer or shorter periods are also possible. The factory produces thin-film modules in a factory that is based on a job-shop principle. The challenge of the used technology and the factory are twofold. As with other factories, the available tool-set is characterized by a considerable amount of non-redundant process equipment. The other challenge is technology-related. In order to ensure a high throughput, the work-in-progress (WIP) in the line has to be high in order to avoid stand-by times. Contrary to this, the interval between some processes should not exceed a specific time-span, while other processes also require a minimum interval. This conflict of objectives requires further analysis.

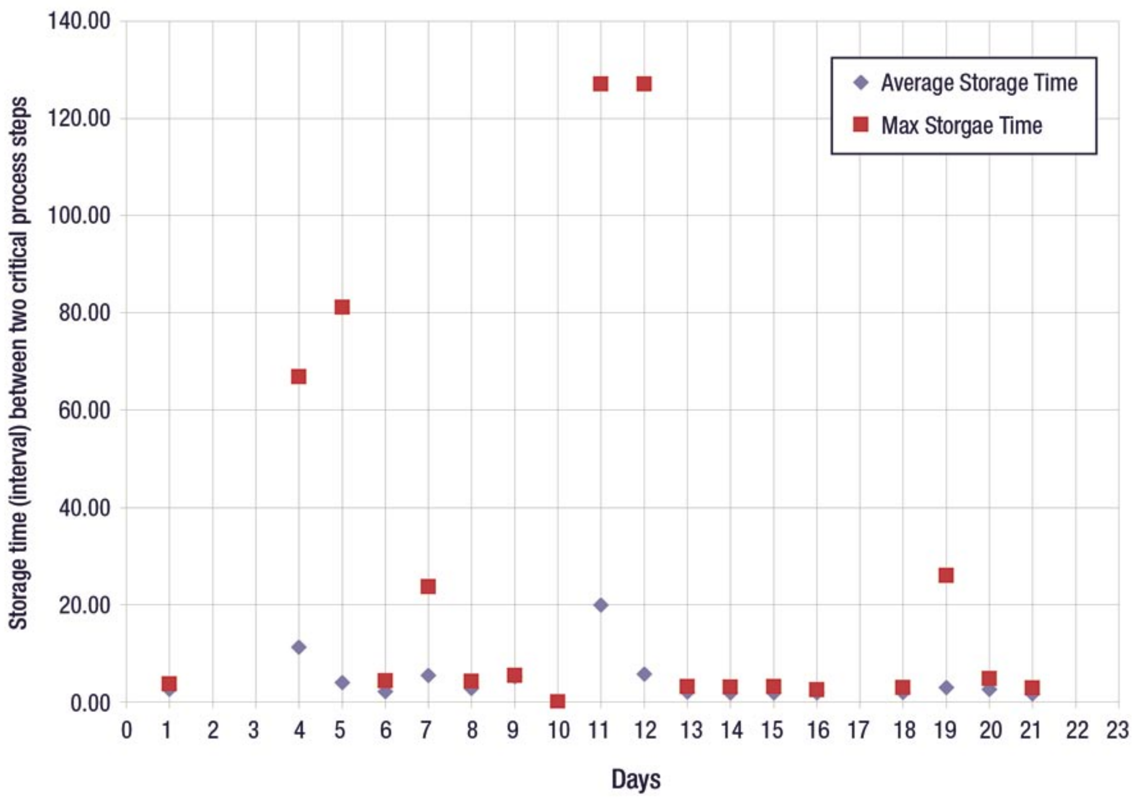

Figure 5. Storage time (interval) between two critical process steps.

The factory operates two major bottleneck processes as shown in Figure 4. During the ramp-up phase, the factory had lulls in operation of 1-2 days to allow for technological and logistical adjustments. Because of the bottleneck processes, the throughput is not stable and it is clear that the succeeding process frequently has to work off the surplus from the preceding process. The preceding process therefore needs to be stopped to allow reduction of the stored substrates.

The balancing of the WIP is difficult to achieve, at least during the ramp-up phase. Therefore, the intervals between the processes cannot be maintained. Figure 5 shows the storage time (interval) between two critical process steps. The substrate should not exceed a time-span of a few hours. However, this time-span is frequently exceeded; some days the substrates have to wait several days before the next process starts. This can be accepted during the ramp-up of the factory, but it has to be managed for constant operations.

Summary

In the future, we will have a much better comprehension of production processes and influences on module performance. Dependencies and influences of the processes will play a larger role in achieving a high and constant level of module performance. Alongside these technological advantages, factories will also grow in capacity, requiring a detailed planning and evaluation of material flow systems. With the proposed methods and tools, the planning and optimization of a factory can be carried out efficiently. This will not only support the factory in question, but will hold great benefit for future factories in the precision of their planning and configuration.

About the Authors

Kevin Reddig is a team leader at Fraunhofer IPA, which he joined in 2002. He received an M.S. degree in industrial engineering from the Universität Karlsruhe (TH). He works in the field of factory automation including equipment automation, material flow solutions and data modelling and processing. He has experience in hardware and software automation projects from both the photovoltaic and semiconductor industries.

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