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Hyeonsik Kim[1], Byoung K. Choi[1*], and Hayong Shin[1]

[1] Department of Industrial and Systems Engineering, KAIST, Daejeon, Republic of Korea
{hyeonsik.kim, bkchoi, hyshin}@kaist.ac.kr

Abstract. In an electronics fabrication line, processing devices are arranged as a network of *inline cells*. Recently, the use of simulation has evolved into *online simulation*, which is used in simulation-based operational management, from the traditional *offline* analysis of facility layout and dispatching rules. An online simulation starts with the *current state* of the manufacturing facilities at any point of time. This paper presents a systematic procedure for building activity cycle diagram (ACD) models of homogeneous job shops having inline cells. In order to demonstrate the effectiveness of the proposed approach, an ACD model was developed for a simple homogeneous job shop having bi-inline cells and a dedicated simulator was also developed.

Keywords: Production simulation, Activity cycle diagram, Homogeneous job shop, Inline cell, Online simulation

1 Introduction

In an electronics fabrication line (Fab), such as a flat panel display (FPD) production line [1] or a semiconductor fabrication line [2], processing devices are arranged as a network of inline cells. An *inline cell* consists of a small number of processing devices and an inner conveyor system that carries individual work-pieces through the processing devices along the conveyor belt [2]. Unlike a table-type machine that processes one work-piece at a time, an inline cell processes a batch of work-pieces simultaneously: each work-piece is loaded at its loading port with an *inter-loading time* (called *takt time*) and travels through the inline cell for a duration of *flow time* to be unloaded at the unloading port. Inline cells in a Fab are usually grouped into a number of *stations* (called *inline stockers* in a FPD Fab or *bays* in a semiconductor Fab) and they are connected by an *automated material handling system* (AMHS) in which cassettes containing individual work-pieces (e.g., glasses or wafers) are transported in the Fab.

The inline cells are largely classified into two types: *bi-inline cells* and *uni-inline cells*. This classification is based on whether the work-pieces are loaded and unloaded in the same port: In a bi-inline cell, work-pieces are loaded at a *loading port* (called the *in-port*) and are unloaded at a separate *unloading port* (called the *out-port*) of the cell; in a uni-inline cell, work-pieces are loaded and unloaded at the same port (called the *in/out-port*). A new (unfinished) work-piece is loaded from a 'new' cassette in the cell; a finished work-piece is unloaded from the cell into an empty cassette. Fig. 1 shows a portion of a (hypothetical) FPD Fab in which all the inline cells are of bi-inline type. There are eight bi-inline cells (PH: photo-lithography; ET: etching; CLN: cleaning; DEP: deposition) grouped into two stations (i.e. inline stockers). The two stations are connected by a pair of uni-directional conveyors. This kind of job shop consisting of the same type of equipment is referred to as a ***homogeneous job shop***. A job shop consisting of mixed types of equipment is referred to as a *heterogeneous job shop*.

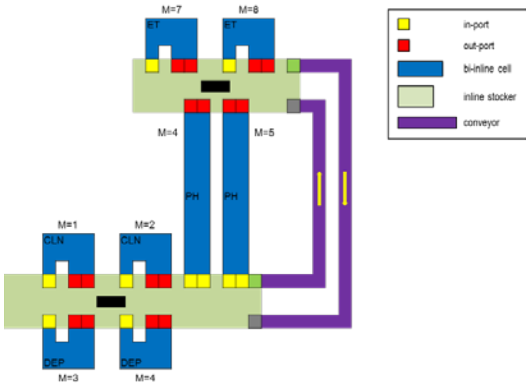


Fig. 1. Layout of a portion of a hypothetical FPD Fab

Recently, the use of a simulation has evolved into the day-to-day operational management of facilities, from the traditional *offline* analysis of facility layout and dispatching rules [3,4,5]. *Online simulation* is used in simulation-based operational management. An online simulation starts with the *current state* of the manufacturing facilities at any point of time [6], and it provides the stakeholders with the ability to evaluate the capacity of the facility for new orders and unforeseen events, and to predict the expected delivery times and changes in operations [4].

Many commercial simulation packages have been introduced to simulate a production system. ASAP (AutoSched AP™) is one of the most popular tools for production simulation [7,8,9]. More recently, ManPy, a semantic-free open-source discrete-event simulation package, was also used in developing a job shop simulator [10]. However, a simulator implemented with a simulation package generally has less flexibility than one implemented based on a well-defined formal modeling tool such as an *event graph* or *activity cycle diagram* (ACD) [11]. Indeed, the event graph is widely used in modeling and simulation of job shops. Notable examples include event graph modeling of a homogeneous job shop with bi-inline cells [12] and event graph modeling of a heterogeneous job shop with inline cells [13]. However, these event graph models are not suitable for an online simulation because representing the current state of a real system as the initial state of the event graph model is difficult.

This paper presents a systematic procedure for building ACD models of homogeneous job shops having inline cells. *Parameterized ACD* (PACD) [11, 14] is used to build the models of the homogeneous job shops. Compared to the event graph modeling approach [12, 13], the ACD modeling approach presented in this paper has some distinctive advantages: The ACD model is 1) easier to build and validate, 2) more intuitive so that a layman can understand the model more easily, and 3) suitable for online simulation because the current state of a real job shop can easily be reflected in the model. In order to demonstrate the effectiveness of the proposed approach, a PACD model was developed for a simple homogenous job shop having bi-inline cells and a dedicated simulator was developed to make simulation runs with input data.

2 ACD Modeling of Inline Cells

Fig. 2 is a schematic description of bi-inline cells in FPD Fab. It is used as a reference model from which an ACD model is to be obtained. An arriving cassette ***enters*** the *cell queue* (Q) of the inline cell, and the cassettes in the queue are ***loaded*** on the *in-port* (PI) if there is room. The ***glass loading*** operation is performed by the *track-in robot* (TI) to load the glasses into the inline cell. The loaded glasses are ***processed*** until they reach the end of the line where the ***glass unloading*** operation is performed by the *track-out robot* (TO), which puts the finished glasses into an empty cassette on an *out-port* (PO). When the unloading cassette becomes full, it is removed so that an empty cassette can be ***supplied***. A cassette that is emptied at the loading section should also be removed to make room for the next arriving cassette.

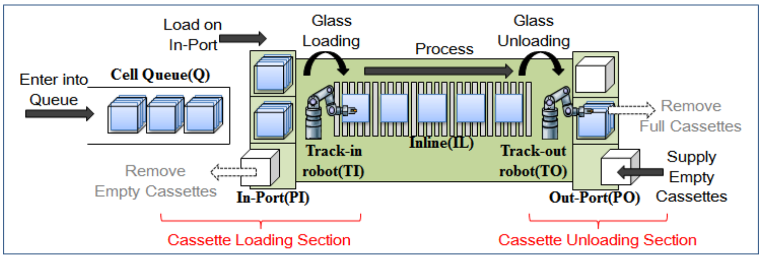


Fig. 2. Reference model of bi-inline cells in FPD Fab

Fig.3 shows an ACD model of the bi-inline cell given in Fig.2. The activities in Fig.2 are modeled as regular activities (solid-line rectangle) in the ACD model:

— Enter (for 'enter into queue' in Fig.2) with activity time t_E (inter-arrival time);
— LoadPI (load a cassette on In-Port) with t_{LPI} (time for loading a cassette at In-Port);
— LoadG (glass loading) with t_L (time for loading all glasses in a cassette);
— ProcessFG (process the 1st glass of a cassette) with t_E (inter-arrival time).
— UnloadG (glass unloading) with t_{TIO} (track-in/out time for a cassette of glasses);
— SupplyEC (supply empty cassettes) with t_{SEC} (time for supplying empty cassette).

The ACD model contains a *computation activity* (dotted-line rectangle) and an *instant activity* ('thin' rectangle) as well. A *regular activity* has a time delay value denoting the activity duration. A *computation activity* is used for computing variables without time delay. The table in Fig. 3 shows detailed computation actions for the computation activity ProcTime (If the job type of the current cassette differs from the last cassette id lastID, a set-up time t_S is added). An instant activity denotes an event such as the start of an activity. There are two parameters in the ACD model, j for job type and p for processing step.

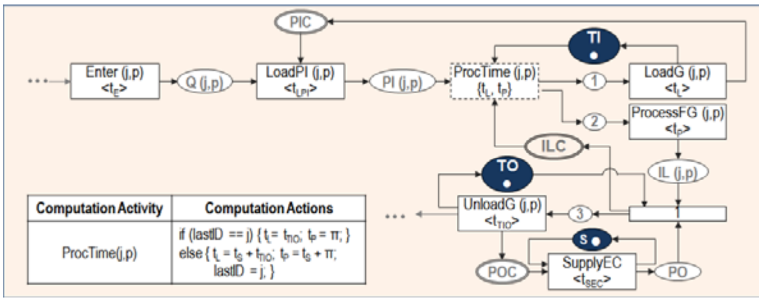


Fig. 3. ACD model of the bi-inline cell in Fig.2

Queues in the ACD model are classified into four types: *Entity queue* (solid line circle) for the number of entities, *resource queue* (intaglio circle) for the number of available resources, *capacity queue* (double-line circle) for the number of available seats, and *instant queue* (small circle) in which tokens do not stay.

- Entity queues are Q (cassettes in the cell queue), PI (cassettes in the In-Port), IL (cassettes in the inline), and PO (empty cassettes in Out-Port);
- Resource queues are TI (track-in robot), TO (track-out robot), and S (empty-cassette supplying system);
- Capacity queues are PIC (capacity or available slots in the In-Port), POC (available slots in the Out-Port), and ILC (available slots in the inline).

Let N_{PI}, N_{IL}, and N_{PO} denote the capacities of In-Port, Inline and Out-Port, and then the following relations should hold: N_{PI} = PI + PIC; N_{IL} = IL + ILC; N_{PO} = PO + POC

Fig.4 shows an ACD model of a uni-inline cell where the *regular* queue PU is the number of cassettes in the in/out port region of the uni-inline cell and the *capacity* queue PUC denotes the number of available ports in the in/out port region. The token in the *resource* queue TIO is used either by the LoadG activity or by the UnloadG activity (LoadG has a higher priority).

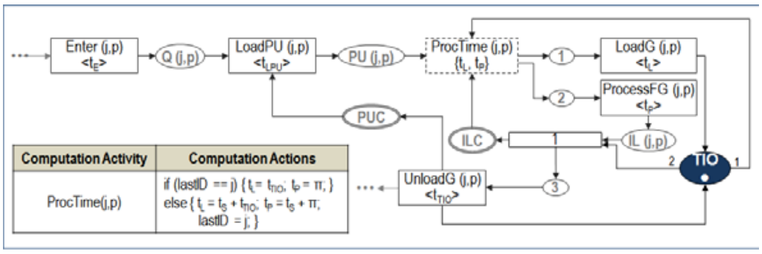
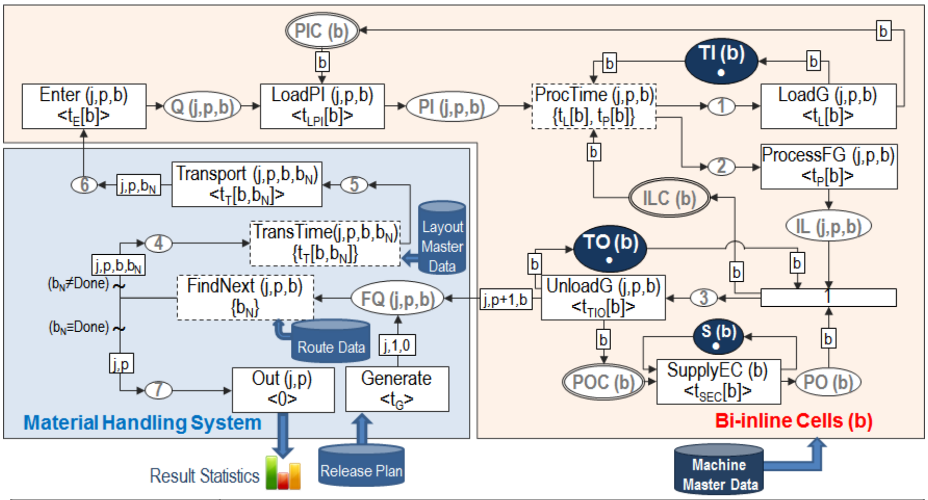


Fig. 4. ACD model of a uni-inline cell

The behavior of a uni-inline cell is identical to that of a bi-inline cell, except loading and unloading of glasses are done at the same port and track-in and track-out operations are performed by the same robot (track-in/out robot). Also, in a uni-inline cell, there is no need for supplying empty cassettes because the finished glasses are unloaded to the cassette from which the glasses were loaded.

3 ACD Modeling of Homogeneous Job Shop having Inline Cells

This section describes how to build an ACD model of a homogeneous job. Fig. 5 shows an ACD model of a job shop consisting of a number of bi-inline cells and a material handling system. The bi-inline cell model of Fig.3 is parameterized with parameter ‘b’ and then connected to the ACD model of the material handling system to obtain a *parameterized* ACD (PACD) model of the homogeneous job shop.

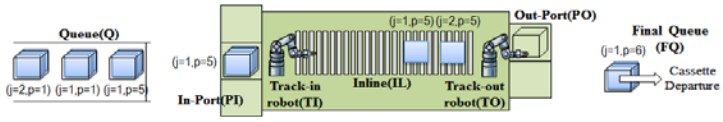


Computation Activity	Computation Actions
FindNext(j,p,b)	b_N=NextEQP(j,p); //NextEQP(j,p): Return EQP ID for j-type and p-step job.
TransTime(j,p,b,b_N)	int sour=Station(b); int dest=Station(b_N); t_T[b,b_N]=t_{SD}[sour, dest]; //Station(b) = the station ID containing b.

Fig. 5. Parameterized ACD model of a homogeneous job shop having bi-inline cells

In the material handling part of the PACD model, arriving cassettes are generated and stored in the entity queue FQ by the Generate activity based on the Release Plan. A bi-inline cell is selected for the generated cassette at the *computation activity* FindNext according to the Route Data. The transporting time t_T from the current location ‘b’ to the target bi-inline cell ‘b_N’ is then computed at the computation activity TransTime referring to the data in the Layout Master Data. Finally, the cassette is transported to the target cell by the regular activity Transport. A cassette containing glasses processed at an inline cell is also stored in FQ, and then it is routed to the next inline cell by the Transport activity or disposed by the Dispose activity if it has completed all the processing steps.

The upper diagram in Fig. 6 shows an example of the *current state* of a bi-inline cell. There are seven cassettes with glasses and one empty cassette in the diagram: three cassettes in Q, one in PI, two in IL, and so on. The cassette in PI, for example, contains glasses of type-1 (j=1) waiting for the 5th processing (p=5). Currently, both robots are idle (TI=1, TO=1). The current state data of the bi-inline cell 'b' can be summarized as shown in the *Current State Table* in the middle part of Fig.6.



Current State Table

Machine ID	Entity Queue					Resource Queue	
(b)	FQ	Q	PI	IL	PO	TI	TO
b	(1,6)	(1,5),(1,1),(2,1)	(1,5)	(2,5), (1,5)	2	1	1

Initial Marking Table

Machine ID	Entity Queue					Capacity Queue			Resource Queue	
(b)	FQ	Q	PI	IC	PO	PIC	ILC	POC	TI	TO
b	(1,6)	(1,5),(1,1),(2,1)	(1,5)	(2,5), (1,5)	1	2	3	1	1	1

Fig. 6. Procedure for initializing state of bi-inline cell #b from current state

Finally, the *Initial Marking Table* shown at the bottom of Fig.6 can be construccted automatically from the *Current State Table*. Each entry in the *capacity queue* column is computed by subtracting the number of cassettes from the capacity value in the queue (e.g., PIC = 3 – |PI| = 3 – 1 = 2). The ability to obtain the initial marking values from the current state data of the Fab makes it easier for the ACD model to be used in an *online simulation* for real-time operation management.

If the bi-inline cell part of the PACD model in Fig.5 is replaced by a PACD model of uni-inline cell (See Fig.4), we obtain a homogeneous job shop having uni-inline cells. Further, if we connect both the bi-inline PACD model and uni-inline PACD model to the same material handling model of Fig.5, we can obtain a PACD model of a heterogeneous job shop.

4 Implementation

This section presents the results of implementing a dedicated simulator executing the PACD model (See Fig.5) of a homogeneous job shop having bi-inline cells. The development of the dedicated simulator has been explained in detail in the literature [11]. The dedicated simulator implemented in C# language is posted at http://www.vms-technology.com/ (Publication menu). The simulator is set to start with an empty system (i.e., all initial markings in the entity queues are set to zero) for the sake of simplicity, which makes it an offline simulator. However, if we set the initial markings to real-time WIP values, it becomes an online simulator.

Tables 1 and 2 show the route data and machine master data, respectively, for a homogeneous job shop having bi-inline cells (See Fig.1). In the experiment, 140 cassettes are released at time 0: 10 cassettes of type-2 jobs (glasses), 20 cassettes of type-1 jobs, 70 cassettes of type-2 jobs, and 40 cassettes of type-1 jobs.

Table 1. Route data for experiment

	Step-1 (p=1)	Step-2 (p=2)	Step-3 (p=3)	Step-4 (p=4)	Step-5 (p=5)	Step-6 (p=6)	Step-7 (p=7)	Step-8 (p=8)	Step-9 (p=9)	Step-10 (p=10)	Step-11 (p=11)	Step-12 (p=12)	Step-13 (p=13)	Step-14 (p=14)	Step-15 (p=15)	Step-16 (p=16)	Step-17 (p=17)	Step-18 (p=18)	Step-19 (p=19)	Step-20 (p=20)
Type-1 (j=1)	{1,2}	{3,4}	{5,6}	{7,8}	{1,2}	{3,4}	{5,6}	{7,8}	{1,2}	{3,4}	{5,6}	{7,8}	{1,2}	{3,4}	{5,6}	{7,8}	-	-	-	-
Type-2 (j=2)	{1,2}	{3,4}	{5,6}	{7,8}	{1,2}	{3,4}	{5,6}	{7,8}	{1,2}	{3,4}	{5,6}	{7,8}	{1,2}	{3,4}	{5,6}	{7,8}	{1,2}	{3,4}	{5,6}	{7,8}

Table 2. Machine master data for experiment

Machine ID (b)	Description	Time Data						Capacity Data		
		Enter time (tE[b])	Load-to-inport time (tLPI[b])	Total track-in/out time (tTIO[b])	Flow time (π[b])	Setup time (tS[b])	Supply time (tSEC[b])	In-port (pi[b])	Out-port (po[b])	Inline (n[b])
1	Cleaning-01	0	0	90	180	0	10	1	2	2
2	Cleaning-02	0	0	90	180	0	10	1	2	2
3	Deposition-01	0	0	99	280	0	10	1	2	2
4	Deposition-01	0	0	99	280	0	10	1	2	2
5	Photo-01	0	0	144	800	120	10	2	2	5
6	Photo-02	0	0	144	800	120	10	2	2	5
7	Etching-01	0	0	99	360	0	10	1	2	3
8	Etching-02	0	0	99	360	0	10	1	2	3

The simulation results are presented in Fig. 7. Fig. 7(a) shows the utilization rate of each bi-inline cell. Notice that the pairs of identical machines have the same utilization rates; this is expected because a machine selection rule of 'smallest-queue-length' was used. Trends of increasing TAT (turn-around-time) also can be observed, indicating that the Fab is becoming congested as more cassettes are released. The disconnections (drops and jumps) in TAT curve Fig. 7 (b) are the results of job type changes.

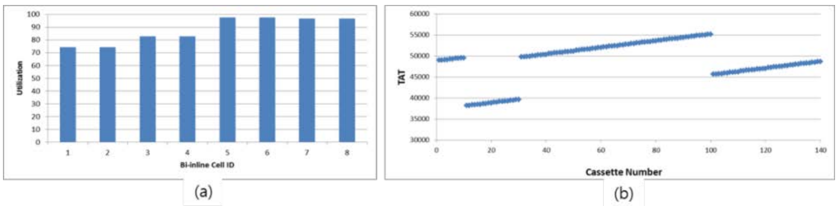


Fig. 7. (a) Utilization for bi-inline cells, (b) Turn-around time for cassette distribution

5 Summary and Conclusions

This paper presents a systematic procedure for building and initializing an ACD model of a homogeneous job shop with inline cells. First, the ACD models of a bi-inline cell and a uni-inline cell are presented. Second, the ACD models of the bi-inline cell and a simplified material handling system are combined to form a PACD model of a homogeneous job shop having inline cells. Finally, the initial marking values for initializing the model are obtained from the current state data of the Fab. The resulting PACD model was verified with a dedicated simulator using sample input data. This model can be implemented within a production simulator, which can be used in an online simulation for real-time operation management. In order to develop a more realistic model, further study is required to accommodate a heterogeneous job shop consisting of different types of inline cells with detailed AMHS.

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