Abstract: Lot scheduling plays a very important role in semiconductor wafer Fab for meeting constraints and allocating reasonable resources to gain higher profit. The complexity comes from various process flows, dynamic manufacturing environment and variant market requirement. To increase average performance of wafer Fabs, the Lot scheduling expert (Production Controller) utilizes her/his knowledge and experience to do the Lot scheduling. How to share and re-use the existing knowledge becomes a major issue in this domain. Therefore, we propose a suite of Lot Scheduling Knowledge-Based System (LS-KBS). We first define a logic-oriented XML-based knowledge representation for knowledge sharing and graphic expression, and then design a visualized knowledge acquisition tool (Logic Map Builder) to elicit the Lot scheduling logics (Logic Map). Three phases are included in our LS-KBS. Firstly, Meta-Knowledge Acquisition Phase is for acquiring the sequence of important knowledge components. Secondly, Knowledge Acquisition Phase is designed to elicit Lot scheduling Logic Map. Finally, Lot Scheduling Phase is developed for knowledge inference by DRAMA to receive relevant facts and generate Lot scheduling result. From the evaluation and the feedback of human expert, we assure that the system not only has the capability to utilize Lot scheduling knowledge as a human expert, but also can be used as a Lot scheduling tutoring system.

Key-Words: Lot scheduling, knowledge acquisition, knowledge-based system

1 Introduction
A lot of scheduling problems occurred in production environment and several approaches have been proposed. However, the scheduling problem of today’s semiconductor wafer fabrication is more difficult than other production systems because of more complex and dynamic manufacturing environment. Since the traditional scheduling solution is difficult to incorporate with human expertise, it can not be easily utilized. Therefore, we propose a knowledge-base system solution.

In a mass production front-end semiconductor fabrication factory (referred to as wafer Fab hereafter), Lot scheduling plays a very important role in wafer Fab, where the product is processed by a batch size, says ‘Lot’. According to the up-to-date customer-oriented market situation, a good Lot scheduling mechanism should help the wafer Fab to meet numbers of constraints and allocate reasonable resources to gain higher profit.

The manufacturing process flows are controlled by an existing information system, manufacturing execution system (referred to as MES hereafter), in most wafer Fabs. As we know, there are more than 300 process steps for a product and over 20 products in a wafer Fab at the same time. This brings a big challenge for Lot scheduling. Many concerns, like product delivery date, machine utilization, Fab throughput, line balance, shared resource, manpower arrangement, process causal restrictions, etc., make the wafer Fab Lot scheduling problem more and more complicated.

The overall complexity of wafer Fab Lot scheduling comes from the various process flows, dynamic and uncertain manufacturing environment and changeful market requirements.

There are a lot of performance criterions in wafer Fab manufacturing and it is difficult to consider all the criterions at the same time. For example, the criteria of product on-time delivery maybe decrease the utilization of machines. Thus, different situations adopt different criterions normally.

To increase average performance, in most wafer Fabs, there would be a specific human expert, called
Production Controller who is responsible for the Lot scheduling job in the manufacturing management department, utilizes on her/his knowledge, including sales order requirement, inventory management, manufacturing status, flow control and process machine usage, and experience to make an adaptive Lot scheduling and generate a suite Lot scheduling logics to prioritize Lots. For avoiding product tardiness, resource waste and machine utilization lost, Lot scheduling is a daily operational planning in semiconductor wafer Fab. According to the short-term production requirement, production controller aggregates overall relative factors to do the Lot scheduling. She/He makes good use of his/her expertise to decide which constraints or heuristics he/she should take. As shown in Fig.1, there are 5 lots are waiting processes by bottleneck machine X. Production controller just concerns the commitment of due date and product cycle time constraints. He/She adopts two sorting procedures - the most recent due date first (EDD) and the shortest queuing time first (FIFO). After series calculations, the prioritized result comes out.

![Fig.1 Progress of Lot Prioritizing](image)

Every domain has its core technology or know-how to represent the value or competitiveness. Our major purpose is to extract and utilize human expertise. Thus, we propose a suite of mechanisms to describe, acquire, reposit, extend and replicate the expertise of Lot scheduling thinking procedures (referred to as Scheduling Logic hereafter). To acquire the Lot scheduling knowledge, a formal knowledge representation (referred to as KR hereafter) is essential and the relationships of knowledge components must be identified. Therefore, we try to come out a complete Lot scheduling knowledge-based system to elicit knowledge and implement a prototype for Lot scheduling.

2 Related Work
Scheduling of wafer Fab is one of the most complex tasks encountered. Some related solutions are classified and introduced in this section. Some theoretical approaches to scheduling strive to search for an optimal solution; however, these approaches suffer from combinatorial complexity that can be proved as an NP-hard problem [4][5].

2.1 Heuristics Approach
The Lot scheduling in wafer Fab often use simple logical rules to decrease the complexity of computation and space. Furthermore, the rules are designed more close to wafer Fab process operations and special environment features. Although it is not necessarily an optimal solution and does not work in other environment, it is still frequently applied due to efficiency calculation and easy understanding.

2.2 Simulation-based approach
Some simulation methodologies developed for waferFab Lot scheduling has the advantages of high fidelity and flexibility, but often comes at an expense of computational requirements and data maintenance. To simulate a complex wafer Fab environment, a large amount data of current wafer Fab must be well-prepared by production controller for the simulation model. As mentioned above, since wafer Fab is a dynamic and uncertain environment, it is very unlikely for production controllers to spend so much time and effort. They would prefer to use heuristic rules and time-saving methodologies [2].

2.3 Machine-Learning Approach
In some researches, machine-learning mechanism is designed to extract Lot dispatching policies from manufacturing execution system [1]. However, the scheduling attributes from MES are finite and the policies must be reviewed by human expert. In this approach, more relevant manufacturing systems must be integrated, like supply-chain system, enterprise resource planning system, machine preventive maintenance system, etc.

2.4 Agent-based Approach
Agent-based approach decomposes wafer Fab lot scheduling job into several intelligent agents and solve the problems in a distributed way [1]. Since agents work autonomously, they have to coordinate with each other by negotiation mechanisms [7].

3 System Architecture of LS-KBS
In traditional approaches, it is difficult to utilize human expertise to solve Lot scheduling problem. Besides, the specific knowledge is also hard to reserve and re-use. For these reasons, as shown in Fig. 2, our approach helps to elicit human expertise appropriately and adopts visualized knowledge representation to simplify the understanding of Lot scheduling process. In the end, the integration with rule-based system and inference engine is made to achieve Lot scheduling process.
3.1 Meta-Knowledge Acquisition Phase

In the same due-date oriented strategy, the Lot scheduling logics are the same in ion implanter and photo-lithograph coater. As long as the Lot scheduling logic of ion implanter was constructed in LS-KBS, the same Lot scheduling logic of coater also can be constructed by referring to the same attributes.

Therefore, we design a meta-knowledge acquisition phase to acquire the ordering of attributes from the production controller. This process helps to generate Lot scheduling logic automatically by referring to existing attributes. Using a user interface designed for the production controllers, they can select the target attributes and the sequence of importance.

To translate meta-knowledge to a Lot scheduling logic graph (referred as Logic Map hereafter), meta-knowledge (MK) translator is proposed. Depending on the requirement of production controller, Logic Map again can be easily adjusted.

3.2 Knowledge Acquisition Phase

Knowledge Acquisition (KA) Phase is the most important process in constructing knowledge-based system. Instead of interviewing production controller, our idea is to elicit Lot scheduling knowledge through a visual KA tool. Before KA process, how to represent Lot scheduling knowledge is a key problem.

Logic Map which can express the Lot scheduling thinking procedures more clearly are easy to maintain and understand by human expert. Therefore, we design a graphic knowledge acquisition tool, named Logic Map Builder, to generate Logic Map.

3.3 Lot Scheduling Inference Phase

According to the Lot scheduling thinking procedures, it looks like a series logics and transforms the knowledge into rules. Thus, we adopt rule-base (a NORM-base model [6]) as our knowledge-base and use of the corresponding inference shell, DRAMA [6], as our inference engine.

4 KR and KA Mechanisms of LS-KBS

As we know, knowledge acquisition (KA) is the most difficult process in constructing knowledge-based system especially in wafer Fab because of many complicated factors and dynamic environment [5]. It is hard to collect relative knowledge through manual interview. In addition, the Lot scheduling human expert owns her/his particular Lot scheduling thinking procedures adaptively for various situations. For these reasons, our idea is to acquire knowledge from production controller via a user-friendly visualized KA tool.

For constructing a specific visual KA tool for wafer Fab Lot scheduling, the essential requirement is to represent the Lot scheduling knowledge which should be shareable and reusable. Therefore, we adopt Extensible Markup Language (XML) data description which is a simple and flexible text format description for data exchange.

4.1 Lot Scheduling Logic Components and XML-Based Knowledge Representation

After discussing with the production controllers, we elicited the expertise, a series of thinking procedures as shown in Fig. 3.

These procedures could be decomposed into a combination of logics as shown in Fig. 4. In other words, the Lot scheduling logics are able to be componentized.

The benefits of componentized logics include:

1. We are able to represent the Lot scheduling knowledge as a graph. This kind of expression is
easier to understand. Besides, componentized logics also contribute to process knowledge acquisition.

(2) Traditionally the Lot scheduling procedures are described in sequence and programmed by hard code in application. The programming effort can be reduced by components reusing and componentized logics are more flexible once the logics are modified.

(3) Componentized logics are corresponding to our rule-base design. Especially we are adopting knowledge-based approach.

Here we classify the logic components and define these components in XML Format in Fig. 5.

![Fig.5 XML-based Representation of Components](image)

### 4.2 Design of 2-Phase KA Tool

In this paper, we design a 2-phase KA process to acquire meta-knowledge and knowledge of human expert for Lot scheduling logics construction. In first phase, the main task is to elicit the guiding knowledge of Lot scheduling knowledge. In second phase, we design a user-friendly KA tool to construct Lot scheduling logic by graph.

- **Meta-Logic Builder**: Meta-knowledge, a kind of knowledge about knowledge, is a control strategy that tells how rules can be applied for knowledge verification and validation in [3]. The rule model type of meta-knowledge determines if the new rule is in the appropriate form to be entered in the knowledge base. In a rule-based expert system, determining if the new rule is in the correct form is called verification of the rule. Determining that a chain of correct inferences leads to the correct answer is called validation. Basically, verification has to do with internal correctness while validation has to do with external correctness.

- **Logic Sequence Builder**: As shown in Fig. 6, a user interface for assigning the importance ordering for Lot scheduling attribute is designed to help the human expert to construct Lot scheduling logic easier. By the assignments, we provide a Logic Translation mechanism to translate the meta-knowledge into Logic Map.

- **Logic Map Builder**: A graphic knowledge acquisition tool, named Logic Map Builder as shown in Fig. 8, is designed to elicit the Lot scheduling logic construction, named Logic Map.

- **Logic Transformer**: For the purpose of flexible inference and knowledge maintenance, we adopt the rule-based mechanism for logic selection as shown in Fig. 9. Therefore, we have to translate Logic Map into NORM-base rule base. NORM is designed by object-oriented concept. Thus, two level rule classes are designed. The top rule class, named logic component rule class, is responsible for logic selection. The bottom rule class, named logic attribute rule class, is a set of attribute classes for the acquirement of logic component rule classes.

![Fig.6 Logic Sequence Builder](image)

![Fig.7. Meta-Knowledge Translation](image)

![Fig.8. Logic Map Builder](image)

![Fig.9. Logic Map – Rule Class Transformation](image)
5 Cases Analysis

For different purposes, production controller comes out different strategies for gaining higher profit. The example of the machine of Lot scheduling is an ion implant machine. Its characteristic is that a dummy testing run is needed once recipe changes. It would cause the resources of materials and manpower are wasted and the machines utilization is decreased if the recipe of machine is changed unreasonably. Thus, production controller must make a lot of effort to keep monitoring the recipe change and to prevent any meaningless dummy run.

In most situations, production controller takes care of the on-time delivery of Lots in wafer Fab production. Besides, they must satisfy the trial process requirement from the engineering department via lot priority assignment. Therefore, in their thinking procedures, they consider the recipe of queuing Lots to realize whether the recipe of Lots is corresponding to current recipe of machine firstly. This process classifies the queuing Lots into two groups. Secondly, they sort the two groups individually by the due date and priority of lots. Two Lot ordering sequences are obtained. As shown in Fig. 10, the queuing Lots are A, B, C, D and E. After the processing, the order of Lot scheduling becomes B, D, A, C and E.

In some special situations, for instance of cost down policy, recipe change makes too much resource wasting. Production takes the recipe change as the most important issue. Then, Cost-oriented Logic Map is maintained as shown in Fig. 11. The same queuing lots are processed in this kind of cost-saving way. The order of Lot scheduling results in D, B, A, E and C. Different result comes from different Lot scheduling logic as well as Logic Map. Logic Map is flexible and powerful for production controller to adjust their strategy.

6 Experiment

The experiment was done in a real wafer Fab. We designed a parallel test with two production controllers and LS-KBS. Our goal is to evaluate the comparison results between LS-KBS and human experts on precision and accuracy.

The experiment was designed to proceed 10 days, i.e. 10 different situations, on the same machine. Two human experts, production controllers, joined this experiment and scheduled the Lots as well as their daily operation. One is a senior production controller and the other is junior one. Besides, the senior production controller maintained the Logic Map in Fig. 12. The testing machine is a metal sputter, which is known as physical vapor deposition and widely used for depositing thin metal layers on semiconductor wafers. The characteristics are: 1) It needs a dummy testing run if recipe changes. The resources of materials and manpower are wasted and the machines utilization is decreased once recipe changing again and again. 2) Relative recipe change is no need to have any extra dummy testing run. It means we had better arrange the Lots of relative recipe into a continuous sequence.

The throughput of this machine is around 5 Lots. We just consider top 5 Lot sequences for evaluation. 2 evaluation indices are designed to verify.

**Precision Testing Index (PTI)**: compared top 5 lots shooting rate between human experts and LS-KBS over 10 situation.
- 100 - Top 5 lots of LS-KBS all are included in top 5 of human experts;
- 80 - Only 4 are included in top 5 of human experts;
... 0 - No 1 is included in top 5 of human experts.

**Accuracy Testing Index (ATI)**: compared top 5 lots process sequence similarity rate between human experts and LS-KBS over 10 situations. We define a distance-weighting function for score calculation. The principle is the higher lot it matches and a higher score it gets. ATI Score Function shows as follows:

\[
\text{ATI Score Function} = \sum_{i=1}^{5} W_i (M_i)^2
\]

where \(M_i\) means the matching of \(i\)-th ordered lot

\(M_i = 1\) if match, \(M_i = 0\) if not match.

\(W_i = 45, W_{15} = 25, W_{10} = 15, W_{6} = 10, W_{6} = 5\)

After testing, the comparison score result comes out as shown in Table 1.

<table>
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<th>Day</th>
<th>PTI Expert 1</th>
<th>PTI Expert 2</th>
<th>ATI Expert 1</th>
<th>ATI Expert 2</th>
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<tr>
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<td>97.25</td>
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</table>

Table 1. Resulting Score of Experiment

According to the result scores, most of the situations are totally matched and only fewer cases are not corresponded. We discussed these cases with our production controllers. In Day 4, the senior production controller explained that one Lot is owned by one of their key customers. It was a special case for winning business so the Lot was arranged to cut in the order. In Day 6, because both of the production controllers received a special request from the engineering Dept. In the morning meeting, they promoted a Lot to 2nd place. In the first case, we suggest the more Logic Components should be appended into the Logic Map to synchronize the Lot scheduling logic. Even the junior production planer didn’t know the tricky point. In the second case, an unexpected event occurred. If the correct priority of the Lot had been maintained, we believed the result would be matched. From the feedback of human experts, we assure the system not only has the capability to reposit and re-use Lot scheduling knowledge, but also can be a Lot scheduling tutoring system.

7 Conclusion

For the purposes of eliciting the hidden knowledge, repositing the expertise and scheduling production lots, we proposed a suite of Lot scheduling knowledge-based system and defined a logic-oriented knowledge representation, based upon XML. In order to acquire the knowledge of Lot scheduling easier, we designed a 2-Phase KA mechanisms for meta-knowledge and knowledge acquisition. The tool provides a user-friendly and graphic interface for knowledge construction.

The comparison of precision and accuracy between the results of our system and human expert was processed. The results of most cases are totally matched. From the feedback of human expert, we proved the system not only has the capability to reposit and re-use Lot scheduling knowledge, but also can be a lot scheduling tutoring system.

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