International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:3, No:10, 2009

Design Considerations of Scheduling Systems Suitable for PCB Manufacturing

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***Abstract*—**This paper identifies five key design characteristics of production scheduling software systems in printed circuit board (PCB) manufacturing. The authors consider that, in addition to an effective scheduling engine, a scheduling system should be able to process a preventative maintenance calendar, to give the user the flexibility to handle data using a variety of electronic sources, to run simulations to support decision-making, and to have simple and customisable graphical user interfaces. These design considerations were the result of a review of academic literature, the evaluation of commercial applications and a compilation of requirements of a PCB manufacturer. It was found that, from those systems that were evaluated, those that effectively addressed all five characteristics outlined in this paper were the most robust of all and could be used in PCB manufacturing.

***Keywords*—**Decision-making, ERP, PCB, scheduling.

I. Introduction

THE manufacturing of printed circuit boards (PCBs) requires a combination of mechanical, electrical and chemical processes [1]. Also, each product is made to order and the complexity and quantity of each job determines the amount of work and the corresponding capacity that every customer order will occupy in the factory. Furthermore, with lead times as short as 24 hours, the need to create and continuously update a master production schedule (MPS) are essential attributes of scheduling systems in PCB manufacturing.

Moreover, the requirements of enterprise resource planning (ERP) systems are specific to this type of industry [2] and production scheduling systems should be able to accommodate to these constraints. However, there is a limited number of practical software applications that can be found. In the academic literature, applications have been developed but are limited to a particular setting ([3],[4]). Others [5] have developed more generic applications by allowing users to compare the performance of a wide range of scheduling rules but cannot be used in a real life setting due to their inherent educational nature. Commercial applications on the other hand, can be available as submodules of a larger ERP system (offering little flexibility) or as standalone versions that are not specific to the PCB industry.

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This paper is twofold, (a) it presents a series of guidelines that software vendors can use to develop robust production scheduling applications in PCB manufacturing; and (b) it can be used by PCB manufacturers to evaluate different software alternatives in terms of the characteristics that are identified in this paper.

II. Goals And Constraints

The aim of this study was to identify the functional characteristics of a production scheduling system for use in a PCB manufacturing setting. To accomplish this goal an evaluation of academic literature, commercial software and a compilation of requirements of a PCB manufacturer were conducted.

This study was carried out in a PCB manufacturing organisation running a dedicated ERP system. The ERP system held engineering, production, quality, inventory and sales data but lacked an engine to generate a feasible master production schedule. The host organisation was not prepared to decommission the system and acquire an alternative one due to the eight years worth of data already stored in the database.

With regards to the nature of the product that the scheduler should be able to cope with, figure 1 shows an example of the sequence of operations required to assemble an eight layer board (although PCBs can be as many as 36 layers). It should be noticed that each level is comprised of one or more subassemblies denominated constructions and each construction is in turn comprised of a series of operations that must be performed in a given order. Therefore, to start the construction in a new level, all the operations in the previous one must be completed first while observing the sequence of operations in each construction. In other words, the constructions in one work order are likely to share the same manufacturing processes resulting in several re-entrant processes to the same equipment unit over the manufacturing life of a product. In addition, all the products are made to order which means that each and every one of the jobs loaded into the factory has its own unique process route. As a result, the equipment capacity is influenced by the complexity of the jobs, the quantity of products per job and their lead times which can vary from 24 hours up to 30 days.

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:3, No:10, 2009

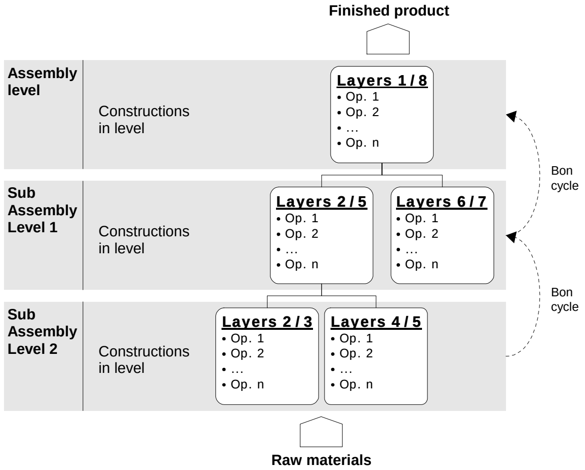

Fig. 1. PCB assembly.

III. Methodology

An online survey of commercially available scheduling systems was conducted to select those with the potential to meet the desired requirements of PCB manufacturing. The authors considered open and closed source applications as well as freeware and retail software. Software vendors were contacted to find out more about the capabilities and applicability of their systems to the PCB industry. Initially, eleven products were considered but only four were found to meet the requirements of the host organisation. All four software vendors demonstrated their products either through face-to-face or online demonstrations and the products were scored against a set of minimum requirements.

The evaluation of the selected scheduling systems was based on a product specification that was produced by the authors based on a review of existing literature, online academic and commercial scheduling demos and on the requirements of the host organisation.

A. Data considerations

The selected software vendors were given a data set with roughly 5,000 operations to be scheduled that accounted for approximately 140-150 customer orders. The planning horizon for these orders, some of which were already in process, was of approximately 2 months. Additionally, an asset register and the shift patterns during which the assets were available, were also provided.

The following assumptions were made regarding the data that had been provided:

- Each operation represented the actions that a production operator had to perform to complete an entire batch of products in the current work centre.
- No set up times were considered and no sequencing of changeovers was required.
- Qualifications or availability of staff were not considered.

The data was stored in electronic spreadsheets for ease of use and manipulation by the software vendors.

B. Product specification

The evaluation of the four selected software solutions was done by means of a product specification outlining the minimum requirements for a scheduling system. In order to produce a specification, the authors (a) conducted a review of existing academic literature related to production scheduling systems, (b) evaluated free demos and whitepapers of commercial and academic scheduling systems, and (c) compiled a set of requirements of the host organisation. As a result, five key design characteristics, shown in figure 2, were identified:

1. A data mapping engine responsible for handling data between the scheduling system and the data source.
2. A scheduling engine responsible for generating a feasible MPS.
3. A means to handle preventative maintenance.
4. A means to run simulations without committing the changes made to the MPS.
5. A suitable graphical user interface.

These five characteristics were found by the authors to be essential in the design of a scheduling system with applications in PCB manufacturing. To validate these findings, the authors tested four commercial scheduling systems using a decision making matrix as shown in table I. It should be noticed that the authors compiled sets of attributes for each of these design characteristics according to the requirements of the host organisation.

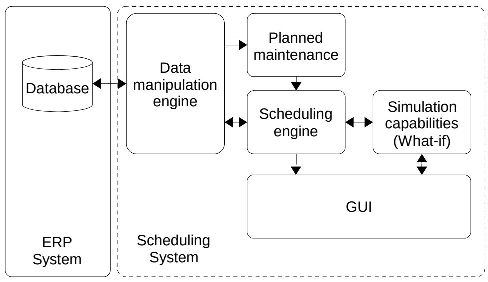

Fig. 2. Design characteristics for a production scheduling system.

IV. Findings

From the eleven scheduling systems originally considered, seven of them were discarded because they did not meet the requirements of the host organisation; i.e. not suited for a job shop environment or with limited number of subassembly levels that they could handle. The remaining four systems were compared against each other by means of the decision support matrix shown in table I. To rate each product against an attribute, the following marking system was used:

0. Not available.
1. Poor functionality.
2. Good functionality.
3. Excellent functionality.

The aforesaid matrix made it possible to compare the products side by side. The following are the most relevant findings that the authors obtained. From this point forward, the products will be referred to as Systems -A, -B, -C and -D.

TABLE I. DECISION MAKING MATRIX.

Code	Attribute	Sys-A	Sys-B	Sys-C	Sys-D
Data mapping	Macro recording	1	1	1	3
	Multiple source formats	1	2	2	3
	Reports	2	2	2	3
	User manipulation	1	1	1	3
	Data mapping Total	5	6	6	12
Engine	Capacity planner	1	3	3	2
	Define shift patterns	2	2	3	3
	Job prioritisation	2	1	3	3
	Lock scheduling window	3	1	3	3
	Parallel machines	1	3	3	3
	Resource overcapacity	2	3	3	2
	Set machine as subcontractor	1	1	3	3
	Sub-assembly levels	2	3	3	3
	Engine Total	14	17	24	22
GUI	Change time-line resolution	3	3	3	3
	Comparison of schedules	3	1	3	3
	Customisation of GUI	2	1	3	3
	Data filtering/sorting	2	2	3	3
	Display queue times	1	1	3	2
	Display working/non-working hours	3	1	3	3
	Equipment hierarchy	1	1	3	3
	Gantt chart	3	3	3	3
	Highlight late jobs	3	1	3	3
	Link operations within orders	3	2	3	3
	Zoom in jobs	2	2	3	3
	GUI Total	26	18	33	32
Maintenance	Built-in	1	1	3	3
	Import maintenance plan	1	1	3	3
	Recurrence of	1	1	3	2
	Maintenance Total	3	3	9	8
Simulation	Run what-if scenarios	3	2	3	3
	Simulation of new orders	2	2	3	3
	Simulation Total	5	4	6	6
Grand Total		53	48	78	80

A. *Data mapping*

In this study, the data mapping engine was found to be essential due to the fact that standalone production scheduling systems were considered only. The robustness of this feature was determined by the ease of the scheduling system to import and export data from one or more sources in a variety of different formats (e.g. SQL, Oracle or electronic spreadsheets among others).

As shown in table I, System -D scored the highest as it was the only one that had a purpose built engine. The user was given the freedom to acquire data from an electronic source and map it to the corresponding table in the scheduler's database. For instance, it was possible to specify the ERP database as the source of the manufacturing operations to schedule and a third party application as the source of the preventative maintenance plan. The remaining three systems did not offer this functionality and all the data manipulation had to be carried out by the software vendors beforehand. Moreover, System-A, a submodule of a larger ERP system which was offered as a standalone product, allowed for no flexibility on the data input as the data requirements had to match those of the ERP system it belonged to.

The authors considered the data mapping engine to be an essential feature in order to acquire data from a variety of sources with little or no interaction from the software vendor. As a result, the customers would not have to depend on the software vendors nor incur in additional support costs if data requirements changed.

B. *Scheduling engine*

Essential to the operation of the scheduler, it is responsible for generating a feasible MPS. The robustness of the engine is determined by its algorithm library [6] and its ability to deal with operational, physical, administrative, work force and process planning issues [7]. The engine should not have limitations in terms of its scheduling horizon. However, the data supplied to the scheduler should not exceed more than two months worth of work otherwise the time required to generate the MPS would be excessive.

All four systems used a limited number of standard dispatching rules, namely the earliest due date and longest processing time (used in System -D only). The authors found this to be interesting because despite the vast number of scheduling models and optimisation techniques available in the academic literature, none of these found their way to any of the systems that were evaluated. Michael L. Pinedo, who has published several papers and a book in the field of scheduling, addressed this issue. In his book and after reviewing the most popular stochastic and deterministic scheduling models found in literature, Pinedo mentions that it is not clear how all this knowledge can be applied to scheduling problems in the real world [5]. The authors recommend the reader to refer to [5], [8], [9] and [10] for a list of differences between real world problems and theoretical models, and to [11] and [12] for an overview of the complexity found in the realm of production scheduling in practice.

In terms of their applicability to the PCB manufacturing industry, none of the four systems was specific to this sector but had applications in a variety of industries; i.e. automotive, steel and electronics sectors. However, Systems -A and -B had limitations in the number of subassemblies they could handle as these were more suited to a flow shop. Also, System –B had a scheduling horizon of one month only which meant that it was not possible to determine the due date for an order if it was completed outside this one-month window. Systems –C and -D did process the data effectively and could therefore be used to schedule the operations found in PCB manufacturing.

C. *Preventative maintenance*

This characteristic was found to be essential for scheduling as preventative maintenance has a direct impact on the available capacity. A planned maintenance calendar should be imported but no maintenance data should be sent back to the source. The authors consider that once a preventative maintenance task is planned, it should not be deferred if the task is scheduled together with the rest of the manufacturing operations on a given equipment unit. It should also be noticed that the preventative maintenance data might not necessarily come from the ERP database but from a third party application.

Systems -A and -B did not have a built in feature to handle preventative maintenance. System -C did not have a preventative maintenance feature per se but did allow for an equipment unit to go offline for a given period of time. System -D was the only product capable of handling a preventative maintenance calendar. As with the previous finding, this was an interesting issue because the cost of these systems is in the

£25K to £30K range plus an annual license fee. For that price, it was expected that a product meant to schedule all the operations in a factory could be able to cope with events that reduced the available capacity in the factory. Moreover, if the quality of the products was to be guaranteed, the condition of the equipment had to be optimal and therefore a preventative maintenance plan should had been scheduled in conjunction with the customers orders.

D. Simulation capabilities

A scheduling system should allow the users to run offline simulations to study the impact of changes made to the original MPS and support the decision making process. Once a scheduling system generated an MPS, users wanted to determine either the effects of changes made to customer order due dates or of loading new orders into the factory. This was a specific requirement of the host organisation and since all four systems had this capability, it was determined that the ability to run simulations was an essential characteristic of a scheduling system.

E. Graphical user interface

According to [5], [6] and [13], the success of a scheduling system is determined by an intuitive, simple, easy to use and customisable graphical user interface (GUI). The authors also emphasised on the importance of displaying data by means of Gantt charts as well as on the importance of comparing the customer due dates against the scheduled completion dates. There were differences observed in the way these systems allowed the user to access, manipulate and view the data which in turn defined the friendliness of the GUI. For instance, systems -A and -B required the user to navigate through several windows as opposed to systems -C and -D.

It is important to highlight the difference between the GUI of a scheduling system and that of the ERP shop floor module. Managers and production supervisors should be the only people allowed to have access to the scheduling system. Therefore, the GUI would have to be designed to match the information requirements of supervisors and managers, not those of the production operators. More importantly, the ability to commit the changes made to the MPS and update the ERP database should be limited to, preferably, one person only to ensure the integrity of the schedule.

V. Conclusion

The authors have identified five main characteristics that need to be considered in the design of a scheduling system with applications in PCB manufacturing. Furthermore, for each design characteristic, a set of attributes could be defined to match particular requirements of a PCB manufacturing organisation. Through the use of a decision making matrix listing the attributes of each characteristic, the authors concluded that the most robust scheduling systems were those that addressed all five design issues.

It was also concluded that the capability of handling a preventative maintenance calendar using a built-in module was limited to one product only despite of the importance that maintenance has on the available equipment capacity. Nevertheless, those systems with no such module were also able to process planned maintenance events but required the software vendors to manipulate the data in order to be effectively processed.

Additionally, none of the scheduling systems that were evaluated, implemented theoretical models found in the realm of scheduling but made use of standard rules such as earliest due date and longest processing time.

Finally, the choice for PCB manufacturers to acquire a scheduling system was found to be limited to a rather small number of alternatives. Furthermore, the authors concluded that only two of the software applications considered in this study were robust enough to be used in PCB manufacturing.

Acknowledgment

The authors would like to thank Stevenage Circuits Ltd. for their co-operation on the study.

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