Summary of Proposed Research Program for Doctor of Philosophy

1. Title

Scheduling of Batch and Mixed Batch/Continuous Process Plants using Petri-nets

2. Abstract

Scheduling with the meaning of allocating jobs to resources in a certain amount of time is an important concept in chemical industries. Effective scheduling of operations in batch processing plants has potential for high economic returns. A schedule determines the optimal input sequence of jobs and resource usage for a specific objective and the complete scheduling method should formulate the problem comprising constraints explicitly and concisely. Production scheduling problems are complex and have been shown to be NP-hard problems [1]. However mathematical formulation and optimal solution methods are still difficult to derive and severely inhibit the attainment of these potential economic benefits. Petri-nets provide a promising technique to solve many difficult problems associated with modelling. Petri-net, as a graphical and mathematical tool, provides an applicable environment for the modelling and design analysis of many systems [2]. As a graphical tool, it can help to visually formulate the problem similar to its flow sheet. As a mathematical tool, Petri-nets can be used to systematically formulate the model used in optimisation and control problems [3]. These formulations are famous for their solid theoretical base and clear syntax [4]. There is much research done on solving scheduling problems for plants, which contain either batch or continuous processes, but there is a substantial lack of research on scheduling the mixed batch/continuous processes. The purpose of this research is to find a suitable type of Petri-net to model and schedule the hybrid systems (mixed batch/continuous systems). In order to find an optimal solution, branch and bound and heuristic algorithms will be developed for scheduling of both multiproduct and multipurpose plants, which are modelled through Petri-nets. The developed algorithm will be applied to case studies of a sugar mill plant and a tyre production plant, which are hybrid systems, and the results will be compared with those of the previous methods. The project will involve extension research on the most suitable type of Petri-net to model mixed batch and continuous plants and the assessment of different search strategies to find the optimal or near optimal schedule. A tyre production plant, which contains mixed batch/continuous structure, will be also considered as an industrial case study in the project.

3. Objectives

The aim of this research is to achieve the following objectives:

1. Development of an algorithm based on Petri-net modelling to schedule multiproduct/multipurpose batch processes and compare the results with those from traditional methods.
2. The most suitable type of Petri-net based modelling and optimal scheduling of operations in mixed batch/continuous plants will be developed in order to:
   - Generate a generic modelling approach to accommodate complex scheduling problem formulations.
   - Develop solution algorithms which rely on simple, computationally inexpensive and efficient combination of heuristic and timed Petri-net execution methods.

- Compare the proposed approach with alternative methods for scheduling of this group of processing plants.

3. Investigation and proposal of different search methods to find the optimal schedule.
4. The efficiency of the proposed research will be investigated through:
   - Application of the developed method to simulation examples.
   - Implementation of the developed method to an industrial sugar mill plant.
   - Implementation of the developed method to an industrial tyre production plant.

4. Background

The optimal scheduling of processing plants has traditionally been formulated as Mixed Integer Linear or Nonlinear Programming (MILP or MINLP) problems [5] [6]. The methodologies allow the incorporation of almost any constraints in the problem formulation, but the solution algorithms suffer from combinatorial complexity. The inclusion of nonlinearities as well as integer variables creates a particularly difficult problem. To improve the combinatorial efficiency, heuristic search algorithms are often adopted [7], which tend towards finding good solutions. The major problem with these algorithms is that they usually end up in local optima. As a remedy, stochastic global optimisation techniques (simulated annealing and generic algorithms) have been proposed [8] [9]. These algorithms have proven to be efficient in the optimisation problems that are dominated by a combinatorial element. Furthermore, they are not as much affected by nonlinearaties and complex objective functions as mathematical programming algorithms. However, it is quite difficult to include complex constraints into their internal representation to ensure the feasibility of the generated schedules.

The mixed-integer techniques have also been shown to have great difficulties in dealing with mixed batch-continuous processes, and systems with variable cycle time [10]. Due to the problems that mixed-integer programming techniques have in dealing with complex scheduling, further research is required to investigate alternative strategies to attack these difficult scheduling problems.

More recently, to easily formulate the scheduling problem, a combinatorial technique using a graph representation has been proposed [11] [12]. This technique was then extended to the short term scheduling of multipurpose batch plants [13]. However, the main problem with this method is that it can only handle unlimited or no intermediate storage cases. While these developments are acknowledged, it should be also considered that almost all of these researches have been done for plants which contain either batch or continuous process and research into the scheduling of mixed-batch/continuous process plants is not so evident.

The most recent research that has been carried out in this area [10] was motivated by an existing scheduling problem in the mixed batch/continuous sugar mill plant. In that work the problem was tackled by uniformly discretising the horizon time and then applying set implementation method. Although a substantial reduction in the complexity of the problem was achieved, there were still a various number of constraints that should be defined and the optimal schedule could not be guaranteed. In this proposal the most suitable type of Petri-net will be proposed to model and schedule industries, which contain both batch and continuous processing units. A Petri net is a particular kind of bipartite directed graphs populated by three types of objects: places, transitions and directed arcs. Each place may potentially hold non or positive number of tokens, pictured by small dots.

Petri-net approaches have proven to be promising in solving many difficult problems associated with the modelling, formal analysis, and design of discrete event systems [14]. The following properties distinguish Petri-net from other tools to be used as a great modeling tool:

1. Boundness and safeness, which indicates capacity. The chemical plants or manufacturing systems in general whose model can not be bounded may result in an infinite WIP (Work In Process).
2. Liveness, which implies that the system can work successfully or on the other hand, it is always possible to do the operation for which the system was designed. Safeness and liveness of marked graphs have been first investigated by [15].
3. Reversibility with the intention of reaching desirable states. It guarantees that it is always possible to return to the initial state from the current state. This is necessary for maintenance, tool adjustments or changes in production.
4. Conservation, which means that tokens are neither created nor destroyed.
5. Mutual exclusion characterizes the impossibility of having more than one event occur at the same time.

One of the major advantages of using a Petri-net model is that the same model can be used for analysis of behavioural properties and performance evaluation, as well as systematic construction of discrete event simulators and controllers. The firing rules of transitions in a Petri-net model make the scheduling problems modeled by Petri-net consider the resource use and product sequence decisions. Material handling action and storage policy can easily be described by using a Petri-net for scheduling of manufacturing systems. Petri-nets have already been used to model and analyse discrete manufacturing systems, simple production lines with buffer machine shops, flexible manufacturing systems, automated assembly lines, intelligent machines and robots, and implementation of supervisory control [16]. More recently, Petri-net techniques have been developed for the logic modelling and coordination control of discrete batch processes [17] [18] [19]. In order to solve scheduling problems with different times of processing, timed Petri-net is introduced. Time constants can be included into a Petri-net by associating it either with transitions (called as a Timed Transition Petri-net, TTPN), or with places (called as a Timed Place Petri-net, TPPN). Several studies on timed Petri-net based scheduling of manufacturing systems were also reported [20] [21] [22].

This project will examine both theoretical and practical developments of timed Petri-net based scheduling of processing plant, focusing on those issues that traditional methods cannot handle.

5. Significance

There have been great difficulties in scheduling plants consisting of both batch and continuous units, with limited or no intermediate storage facilities, and with variable batch cycle times. This study intends to address these important problems using a Petri-net based approach. Specifically:

1. The application of Petri-net solutions will be expressed for these classes of problems.
2. Insights will be gained on problem characteristics that allow the efficient use of Petri-net based approaches. Past applications of Petri-nets to solve manufacturing problems have not investigated problem characteristics that arise in a process environment.
3. Different algorithms, which can solve the scheduling problems through Petri-nets, will be developed.
4. All constraints, which have to be written in order to find the best schedule by using the pervious method (MILP), will be considered in terms of firing transitions in Petri-net.

5. The inherent mathematical complexity of mixed-integer based scheduling approaches, and the great difficulty in their industrial implementation, place significant demands on alternative approaches. The advantage of Petri-net based modelling is the ability to develop efficient algorithms with far less mathematical complexity. This provides a profound advancement towards industrial implementation.
6. A mixed batch/continuous sugar mill case study representing the scheduling problems will be formulated by the proposed novel algorithm and formulation.
7. A mixed batch/continuous tyre production plant case study representing the scheduling problems will be formulated by the proposed novel algorithm and formulation.

6. Research Method

Developing a Petri-net based algorithm for scheduling of mixed batch/continuous plants is the major focus of this work and most time will be spent in developing techniques suitable for this class of problems. Because of the particular nature of these plants, also known as hybrid systems, traditional mixed integer techniques encounter difficulties. This research will investigate the use of Petri-nets as described below. It should be noted that batch cycle times can vary, and therefore could be considered as decision variables. To deal with this situation, timed places will be introduced into the Petri-net model and a time interval for each variable cycle time will be attached to them.

The entire mixed batch/continuous (hybrid) plant will be hierarchically modelled in two levels. On the lower level, the batch and continuous sections will be formulated using different Petri-net based methods. The top level is for the coordination and workload allocation of the two sections.

To solve batch plant scheduling problem modelled with Petri-nets, branch and bound method will be used; all possible operations of different sequences can be completely tracked by the reachability tree of the problem in which the branches are the firing sequences of the transitions. The following shows the details of the initially developed algorithm for scheduling of batch and mixed batch/continuous plants using timed Petri-net:

- **S1:** Begin with the initial marking and a large number for makespan (total time until the last job is completed);
- **S2:** With the initial marking check which transitions are enabled. Determine the new markings and the usage time for each unit with respect to the transitions and put them together with the old markings into one result matrix.
- **S3:** If the latest usage time of the units is greater than or equal to the makespan, go to S6.
- **S4:** If the new marking is not equal to the final marking, set the new marking as the initial marking and go to S2.
- **S5:** If the latest usage time of the units is less than makespan, update makespan to this new time.
- **S6:** If all the rows of the result matrix have been assessed, the search is completed; output the makespan and optimum schedule; then stop.
- **S7:** Start checking from the last row of the result matrix upward and find the row in which the associated transition is enabled and has not been fired yet; set the marking of this row as an initial marking and go to S2.

However, even for a simple Petri-net, the reachability tree may be too large to generate as a whole. Instead of generating the entire reachability tree, a heuristic algorithm is developed to generate only the necessary portion of the tree. A* search algorithm is one of the heuristic algorithms which is integrated to firing rules of Petri-net and is used to reduce the number of searches. The following shows the steps of the initially developed algorithm for solving scheduling problems of multiproduct/multipurpose batch plants:

- **S1:** Begin with the initial marking and a large number for makespan;
- **S2:** With the initial marking check which transitions are enabled. Determine the new markings and usage time for each unit with respect to the transitions and put them together with the old markings into one result matrix.
- **S3:** If the latest usage time of the units is greater than or equal to the makespan go to S8.
- **S4:** Compute (for each marking) the maximum between the time remaining for each product in each unit and also the time remaining for each product to be processed (h). Add h to the starting time of the new marking (g), compute f. Put f in the relevant row of the result matrix.
- **S5:** If f is greater than or equal to the makespan go to S8.
- **S6:** If the new marking is not equal to the final marking, set the new marking as the initial marking and go to S2.
- **S7:** If the latest usage time of the units is less than makespan, update makespan to this time.
- **S8:** If all the rows of the result matrix have been assessed, the search is completed; output the makespan and the feasible schedule to this makespan; then stop.
- **S9:** Start checking from the last row of the result matrix upward and find the row in which the associated transition is enabled and has not been fired yet; set the marking of this row as the initial marking and go to S2.

To show the benefit of the application of the above strategies, a multiproduct batch plant consisting of three products (p1 to p3) and two processing units (u1 to u2) is considered. The processing times of each product in each unit are given in Table 1.

Table 1: Processing times (h) of products

Units	Products p1	p2	p3
u1	3.0	4.0	3.0
u2	4.0	5.0	7.0

The Timed Place Petri-net model is shown in Figure 1.

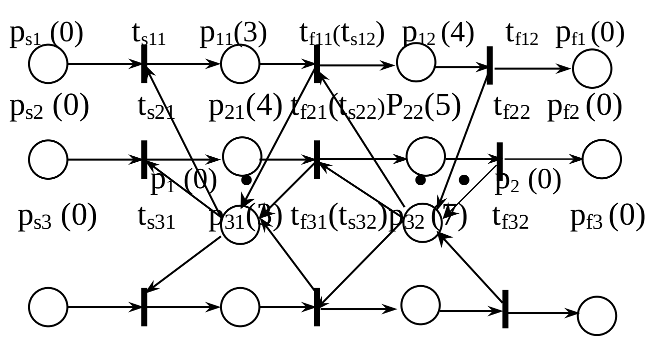

Figure 1: Modeling a batch plant via TPPNs

To solve the scheduling problem of this case through the above algorithm, we only need to have the preceding relationships between places and transitions which are shown by 1 for those transitions which are connected to places and –1 for those places which are connected to transitions and 0 for those places and transitions with no relationships. This can be easily derived from the Petri-net model. The best schedule is illustrated by a Gantt chart in Figure 2.

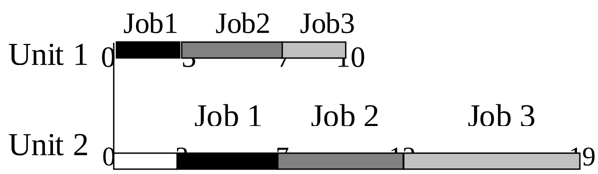

Figure 2: The Gant chart for optimal scheduling (case study 1)

To solve the same problem with MILP methods which is a traditional method for solving these types of problems, the following formulations are needed:

Objective:
min: x6;

Constraints:
+x2 -x1 -4 x7 -5 x9 -7 x11 >= 0;
+x4 -x3 -4 x8 -5 x10 -7 x12 >= 0;
+x6 -x5 -4 x13 -5 x14 -7 x15 >= 0;
+x1 -3 x7 -4 x9 -3 x11 >= 0;
+x3- x1 -3 x8 -4 x10 -3 x12 >= 0;
+x5 -x3 -3 x13 -4 x14- 3 x15 >= 0;
+x7 + x9 + x11 - 1 = 0;
+x8 + x10 + x12 - 1 = 0;
+x13 + x14 + x15 - 1 = 0;
+x7 + x8 + x13 - 1 = 0;
+x9 + x10 + x14 - 1 = 0;
+x11 + x12 + x15 - 1 = 0;
+x3 - x2 >= 0;
+x5 - x4 >= 0;
int x7, x8, x9, x10, x11, x12, x13, x14, x15

As it can be seen, even for solving this small problem, 23 constraints and 15 variables should be defined, while all these constraints have been considered in firing rules of transitions. In this research the effectiveness of the above strategies will be explored through the simulation case studies (e.g., sugar mill plant).

So far the Timed Hybrid Petri-net has been realised as a suitable tool for modelling plants with mixed batch and continuous structure. A hybrid Petri-net is a sextuple $Q = \{P, T, Pre, Post,$

m0, h) where P is a set of places, T is a set of transitions, Pre is the input incidence matrix, Post is the output incidence matrix, m0 is the initial marking and h is called hybrid function and indicates for every node whether it is discrete or continuous node [23]. By using Timed Hybrid Petri-nets, all batch and continuous operations and the storages between them with the associated capacities and the availability of raw materials and all other constraints can be illustrated effectively.

The sugar industry in Australia provides an excellent example of where such technologies can be utilized to greatly enhance operations. The crystallization, centrifugation and drying stages of the process represent a batch/continuous operation with limited intermediate storage.

7. Ethical Issues

This research program does not require testing to be done on humans or animals and does not involve potentially dangerous equipment of any kind.

8. Facilities and Resources

No special resources or facilities are required to complete the study other than Visual C++ version 6 Software, which will be used for simulation..

9. Data Storage

The data storage provisions are outlined in the attached Research Data Management Plan and meet the Curtin University Research Data and Primary Materials Policy.

10. Time Line

The predicted time line for the research is as follows:

Table 2. Predicted time line for the research.

Year and Quarter	Year 1			Year 2				Year 3				Year 4
Task	2	3	4	1	2	3	4	1	2	3	4	1
Literature Review	▲	▲	▲	▲	▲	▲	▲	▲	△	△	△	△
Theoretical development												
Developing a Petri-net based algorithm for scheduling of multiproduct batch plant and Implementation of the developed technique to simulation case studies	▲	▲	▲	△	△	△	△	△	△	△	△	△
Developing a Petri-net based algorithm for scheduling of multipurpose batch plant and Implementation of the developed technique to simulation case studies	△	△	△	▲	▲	△	△	△	△	△	△	△
Finding a suitable type of Petri-net for modeling mixed batch/continuous processes	△	△	△	△	▲	▲	△	△	△	△	△	△
Developing a Petri-net based algorithm for scheduling of mixed batch/continuous plant	△	△	△	△	△	▲	▲	▲	△	△	△	△
Practical development												
Implementation of the developed technique to sugar mill plant	△	△	△	△	△	△	▲	▲	△	△	△	△
Implementation of the developed technique to tire company plant	△	△	△	△	△	△	△	△	▲	△	△	△
Applying different search strategies to find the optimal or near optimal schedule in a mixed batch/continuous plant	△	△	△	△	△	△	△	△	▲	▲	△	△
Documentation and writing thesis	△	△	△	△	△	△	△	△	△	△	▲	▲

△ Low Priority
▲ High Priority

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