An Effective Tabu Search-Based Petri Net Method for Scheduling Crude Oil Refinery Operations with Preventive Maintenance

Husam Kaid

Industrial Engineering Department, College of Engineering, Taibah University, Medina 42353, Saudi Arabia
Email: hkaid@taibahu.edu.sa

Abstract

The short-term scheduling problem (STSP) of oil refinery operations with unreliable distillation units (CDUs) is a NP-hard problem, necessitating a high degree of accuracy and efficient techniques. Developing effective scheduling optimization techniques for oil refineries is a significant challenge. In order to provide solutions to this difficult problem, this study proposes a new hybrid Petri net and tabu search (PNTS) approach with unreliable CDUs to effectively solve this problem. To show the efficiency of the developed approach, an industrial case study is used. The results demonstrate that the developed method efficiently solves the industrial case study.

Keywords
Scheduling, oil refinery, Petri net, tabu search.

1. Introduction

Global market competition and the associated environmental challenges need that companies seek strategies to increase profit, reduce carbon dioxide emissions, and minimize expenses. It has been established that efficient production planning improves both the economy and the environment in high-energy-consuming industries (Al-Sharrah et al., 2001). Process industries, including steel production and oil refining, consume more energy and have a high cost. As a result, it is critical to develop effective strategies for managing a plant's activities efficiently.

Nowadays, a new factory is handled hierarchically, with three levels: process control at the bottom, scheduling in the middle, and production planning at the top. It is well recognized that essentially most industrial plants have optimized their unit performance criteria at the process control level by installing intelligent control methods. Moreover, with the introduction of methods based on "linear programming," planning technology has evolved significantly, enabling the efficient formulation of an optimal plan (Pelham and Pharris, 1996). However, for industrial-scale applications, computationally efficient techniques and related software tools are required at the middle level (Wu et al., 2008c, Honkomp et al., 2000). Indeed, a planner prepares the STSP manually through trial and error (Wu et al., 2008c). With a gap between the upper and bottom levels, the three levels are unable to be combined, leading to an inefficiently run plant (Jaikumar, 1974, Shobrys and White, 2000). Therefore, effective solutions for the STSP must be investigated to develop tools. Since a crude oil refinery is a process flow industry, which makes a major contribution to the economy, this study investigates in detail its short-term scheduling difficulty.

For complicated scheduling problems, heuristic methods such as tabu search algorithms, simulated annealing algorithms, and genetic algorithms are good solutions (Mattfeld and Bierwirth, 2004, Ponnambalam et al., 1999, Sabuncuoglu and Bayiz, 1999, Yang and Wang, 2001). These approaches are only applied to problems with initially deterministic scheduled jobs and no consideration for solution feasibility. To develop the STS for the refinery plant, the number of activities to be performed should be specified, the specific prosesses for each activity described, the time needed for each prosess defined, and the activities sequenced. Moreover, there is no realistic way for determining the feasibility of a schedule. Furthermore, these methods are ineffective for scheduling refineries on a short-term basis. As a result, a novel approach to overcoming this problem should be presented.

The study in (Wu et al., 2008c) divides the STSP of oil refinery operations into two hierarchical subproblems to address the short-term scheduling problem. At the highest level, a refining schedule must be determined by optimizing certain criteria; at the lowest level, a thorough schedule for a given refining operation must be designed. The studies in (Wu et al., 2008c, Wu et al., 2008a, Wu et al., 2008b, Wu et al., 2009) present a heuristic for determining the realizability of a specific refining schedule in (Wu et al., 2008c) using a Petri net (PN) model. Following that, a detailed schedule is proposed. However, without the need for a detailed schedule, that approach cannot establish the feasibility of the refining schedule. Furthermore, no method for quickly constructing a feasible refining schedule is presented in (Wu et al., 2008c). The studies of (Wu et al., 2015, Zhang et al., 2017) represent the STSP as a "hybrid Petri net" and extract important scheduling constraints from this model. The work of (Al-Ahmari et al., 2022) proposes a novel "mixed-integer nonlinear programming" model for STSP of oil refinery operations under unreliable CDUs. The study of (Wu et al., 2022)introduces the scheduling problem of "high-throughput screening" (HTS). First, "resource-oriented Petri nets" are used to represent the HTS. Next, they identify the "transition firing sequence" in order to find the "activity sequence" for a feasible and optimal schedule.

The following are the primary obstacles to designing an optimal refining schedule: 1) optimization of several objectives is required, and 2) continuous and discrete variables combine. To address these restrictions, this study proposes a novel technique for solving the aforementioned extremely difficult problem. To effectively solve the STSP of oil refinery processes with unreliable distillation units, this study builds a new hybrid Petri nets and tabu search (PNTS) technique based on unreliable distillation units.

This study is organized as follows. Section 2 provides a statement for the STSP (Al-Ahmari et al., 2022) using the PN model. The developed method is then shown in Section 3. Section 4 presents the applicability and effectiveness of the suggested method through an industry case study. Section 5 summarizes the conclusions and future works.

2. Problem Description

2.1 Problem Definition

The structure depicted in Figure 1 is a typical oil refinery configuration. As shown in Figure 1, the facility has many "storage tanks" close to the port, "charging tanks" inside the facility, and "distillation units." Production and crude oil activities are two different processes in terms of operations. The port is supplied with crude oil by ships. The oil is then transported to "storage tanks." "Pipelines" are used to move oil from "storage tanks" to "charging tanks." The oil is transported to "distillation units" by "charge tanks." The term "crude oil processing" refers to these operations. Following distillation, the oil is processed in several manufacturing lines to produce a wide variety of components.

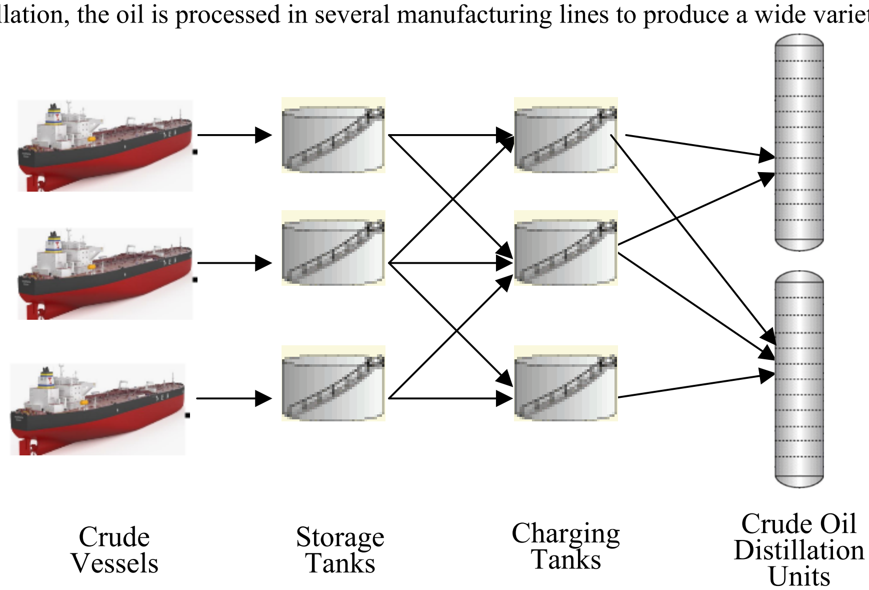

Figure 1. An example of the oil refinery system.

The objective of this research is to determine the challenges with the STSP of oil refinery processes with unreliable distillation units. The management of oil refinery processes is a complex system comprised of continuous and discrete processes. On the one hand, the size of the resulting model must be small in order to make it tractable. Therefore, both continuous and discrete behavior must be effectively modeled.

When implementing the resource-oriented Petri net (ROPN) modeling approach proposed in (Wu, 1999, Wu and Zhou, 2009, Wu and Zhou, 2004, Kaid et al., 2021, Kaid et al., 2020, Al-Ahmari et al., 2020), the model's complexity is proportional to the system's size, as each resource is denoted by a place in the model. This study will use the ROPN modeling approach to represent an crude oil refinery operations by modeling each system resource as a module in order to make the resulting model feasible.

The following assumptions are used to formulate the STSP of oil refinery operations under unreliable distillation units:

1. All crude distillation units are available to process oils at time 0.
2. A CDU is restricted to processing a single kind of oil at a time.
3. A maximum of two CDUs can process crude oil simultaneously;
4. Each oil operation must be performed without interruption;
5. CDUs must operate continuously during the scheduling horizon;
6. Unloading rates, feeding rates, and preventative maintenance intervals are defined and known.
7. No rework allowed for crude oils.

The goal is to figure out how often each process will happen, when each process will start and end, and how much crude oil needs to be moved to the distillation plant.

2.2 Petri Nets Modeling

Due to refinery layouts, there are various scenarios for refineries; some require high fusion point oil processing, while others do not; some require numerous pipelines for oil transportation, while others require only one; and so on. In this section, the Petri net modeling approach is introduced by assuming that there is only one pipeline that can process high fusion oil. In fact, this configuration is extremely popular and very complex. Symbols shown in Figure 2 describe the model. It is a "colored-finite-capacity" Petri net and is described as $N = (P, T, I, O, K, H, M)$, where

1. $P=P_D \cup P_C \cup P_E$: represents the set of places, including discrete places P_D, continuous places P_C, and enforcing places P_E;
2. $T=T_D \cup T_T \cup T_C$: is the set of transitions, including discrete transitions T_D, timed transitions T_T, and continuous transitions T_C;
3. $I: P\times T\rightarrow\{0, 1\}$, $O:P\times T\rightarrow\{0, 1\}$, and $H:P\times T\rightarrow\{0, 1\}$: are the Input, output, and inhibitor functions, respectively;
4. $K(p) \in \mathbf{IN} = \{0, 1,2, \ldots\}$ provides the capacity of place p, i.e., p can contain no more than $K(p)$ tokens at a time;
5. M: represents the marking, where M_0 is the initial marking and $M(p)$ is the maximum number of tokens in place p.

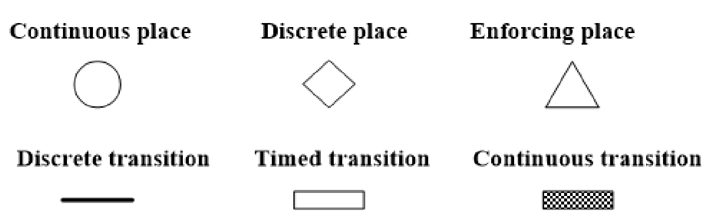

Figure 2. The symbols for the Petri net model.

The output and input places of a transition $t \in T$ are respectively represented as "$t^\bullet = \{p \in P: O(p, t) > 0\}$" and "$^\bullet t = \{p \in P: I(p, t) > 0\}$". Similarly, the output and input transition of a place $p \in P$ are respectively represented as "$p^\bullet = \{t: t \in T \text{ and } I(p, t) > 0\}$" and "$^\bullet p = \{t: t \in T \text{ and } O(p, t) > 0\}$". An ROPN model is built (Wu and Zhou, 2009) for the addressed system using the above-mentioned basic principle of PNs. To accurately model the system, each device (resource) is represented by a Petri net module, which results in an ROPN.

Figure 3 depicts the the oil refinery system under unreliable distillation units using ROPN. Places $p_s \in P_C$ and $p_c \in P_C$ together define the state of a tank. To represent the continuous nature of crude oil, each token is defined to have a real volume. To denote the type of oil, a color must be associated with a token. Thus, a token in $p_s \in P_C$ or $p_c \in P_C$ implies that a tank contains oil of a specific type. The capacity remaining in any state is shown by the place $p_3 \in P_C$. The transitions $t_1 \in T_C$ and $t_3 \in T_C$ correspond to the charging and discharging of a tank, respectively. In Figure 3, the places $p_1 \in P_C$, $p_2 \in P_C$, and $p_3 \in P_C$, shown by different-colored tokens, represent oil-type segments containing various types of oil in a pipeline. Transitions $t_1 \in T_D$ and $t_2 \in T_D$ indicate the direction of oil flow between segments. The transitions $t_{I1} \in T_C$, $t_{I1} \in T_C$, …, $t_{Ik} \in T_C$ represent the entry of crude oil into a pipeline from various storage tanks, whereas the transitions $t_{O1} \in T_C$, $t_{O2} \in T_C$, …, $t_{Ok} \in T_C$ represent the exit of crude oil from a pipeline to various charging tanks. Place $p_4 \in P_E$ indicates the type of oil contained in a pipeline. This means that if a token representing an oil type with a high fusion point exists, both a transition $t_{Ii} \in T_C$ and $i \in \{1, 2, …, k\}$ and a transition $t_{Oi} \in T_C$ and $i \in \{1, 2, …, k\}$ must fire, guaranteeing that the oil with a high fusion point cannot remain in a pipeline without flowing. This adequately describes the dynamic behavior of a pipeline. Because only one of the transitions $t_{I1} \in T_C$, $t_{I2} \in T_C$, …, $t_{Ik} \in T_C$ can fire at a time and only one of them is firing, and only one of the transitions $t_{O1} \in T_C$, $t_{O2} \in T_C$, …, $t_{Ok} \in T_C$ should fire at the same rate, the Petri net module of a can be combined as a macro transition y, as illustrated in Figure 3.
Then, the Petri net modules can be integrated to construct a system Petri net model **y** by eliminating the discrete place, inhibitor arc, and arcs corresponding with the discrete place in the module for a tank, an overall model for the system with one berth, two storage tanks, two charging tanks, a pipeline, and two CDUs can be constructed as presented in Figure 3. In Figure 3, two storage tanks are denoted as $\{t_{11}, p_{1s}, t_{12}, p_{1c}, p_{13}, y\}$ and $\{t_{21}, p_{2s}, t_{22}, p_{2c}, p_{23}, y\}$, whereas the two charging tanks are denoted as $\{y, p_{3s}, t_{31}, p_{3c}, t_{32}, p_{33}\}$ and $\{y, p_{4s}, t_{41}, p_{4c}, t_{42}, p_{43}\}$. Transition $t_1 \in T_D$ generates tanker arrivals that carry oil, while $p_1 \in P_C$ indicates that only one berth is available and only oil can be unloaded in a single tanker. The two CDUs are represented by places $p_3 \in P_C$ and $p_4 \in P_C$. If p_3 contains a token or $M(p_3) = 1$, then the CDU modeled by p_3 is operating; otherwise, it is not. Finally, the following modeling strategy for recovery subnets is designed to represent all preventive maintenance (PM) activities in CDUs: $\{p_3, t_{B3}, p_{PM3}, t_{E3}, p_3\}$ and $\{p_4, t_{B4}, p_{PM4}, t_{E4}, p_4\}$, where p_{PM3} and p_{PM4} denote the places of recovery PM activities for CDU 1 (place p_3) and CDU 2 (place p_4), respectively. t_{B3} and t_{B4} are the beginning times of PM activities for CDU 1 and CDU 2, respectively. t_{E3} and t_{E4} are the ending times of PM activities for CDU 1 and CDU 2, respectively.

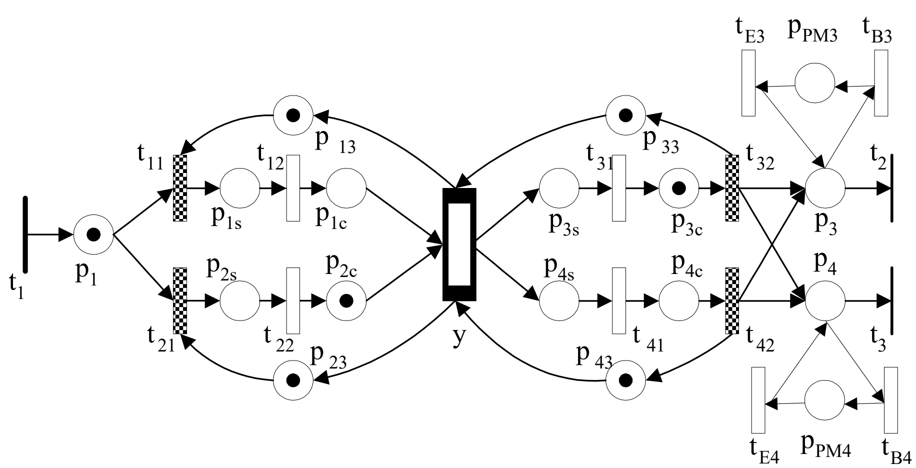

Figure 3. The unreliable Petri net model of the oil refinery system.

3. Tabu Search Algorithm

Tabu search (TS) is a metaheuristic optimization technique, which uses local search techniques for optimization problems (Glover, 1989). Local (neighborhood) search mechanisms examine the local neighbors of a feasible solution to a problem with the aim of discovering a superior solution. Local search techniques have the potential to become mired in suboptimal zones when several solutions are perfectly good. TS improves the efficiency of local search by modifying its fundamental rule. Initially, at each phase, worsening moves may be allowed if there is no feasible improvement. Moreover, prohibitions (called tabu list) are used to prevent the search from returning to previously explored solutions. The execution of TS involves the use of memory structures, which represent the explored solutions. When a potential solution has already been considered within a particular length of time or if it violates a criteria, it is classified as "tabu" (prohibited) so that the method does not examine it once again (Glover, 1989). The following pseudocode provides a simpler form of the TS method as described in (Kaid et al., 2015, Alharkan et al., 2020):

Algorithm 1: Construction of PNTS algorithm.

Input: Unreliable Petri net (N_U, M_{Uo})
Initialization: Let s and s_0 to be the initial and the best solutions, $s_0 = s$ and set the tabu list.
while (not stopping condition) **do**
i. Construct "K" various solutions;
ii. Calculate "K" solutions using the developed unreliable Petri net (N_U, M_{Uo});
iii. Choose the best neighbor s' of "K";
iv. $s = s'$;
v. Modify tabu list and aspiration conditions;
vi. **If** $f(s) < f(s_0)$, **Then** $s_0 = s$;
end while
The best solution s_0.

4. Industrial Case Study

Two CDU 1 and 2 are used in the refinery case study. Three times per month, a plan for the following ten days is constructed. This scheduling horizon will process four different types of oil. Both CDUs are capable of processing any kind of crude oil. Table 1 presents the costs related to the various types of oil and CDUs. During the scheduling horizon, two charging tanks are accessible. First, charging tanks are empty of crude oil. Tanks 1 and 2 supply distillers 1 and 2. Table 2 shows the oil types to be processed and their arrival times for this scheduling horizon, the number of distillation units, a set of charging tanks and their initial oil volume, and the unloading and feeding rates for tanks and distillation units, respectively. The PM requirements for CDUs are listed in Table 3. To solve the industrial case study by using the developed PNTS model, the proposed approach in this paper was coded and implemented using MATLAB R2015a. The optimal solutions of crude oil allocation for case studies 1–4 respectively shown in Figure 4.

Table 1: Operational costs of distillation units used in case study for various types of oil.

CDU	**Oil type**			
	1	**2**	**3**	**4**
1	3	3	5	7
2	1	4	6	5

Table 2: Data of the case study.

Tank	Capacity (Ton)	Feeding rate (Ton/hr)	Unload rate (Ton/hr)	Oil type	Oil arrival (hr)	Volume (Ton)
1	[0 34000]	[0 350]	[0 400]	1	0	30000
2	[0 34000]	[0 400]	[0 400]	2	0	25000
				3	5	16000
				4	8	20000

Table 3: PM parameters for distillation units for the case study.

CDU	**PM Parameter**	
	t_{Bi} **(hr)**	t_{Ei} **(hr)**
1	120	125
2	150	155

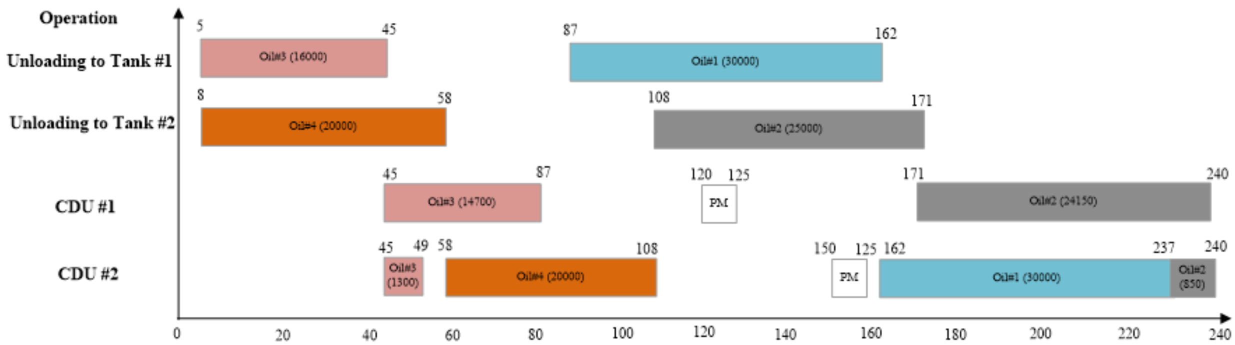

Figure 4. Optimal schedule for the 10-day time horizon of the case study.

5. Conclusion

This paper presents the STSP of oil refinery processes with unreliable distillation units. The STSP is a NP-hard problem that is difficult to solve. Due to the complexity of the STSP, the scheduling process must continue to be conducted manually, and efficient techniques and software tools are required. In order to propose solutions to this difficult problem, this paper develops a new hybrid Petri net and tabu search (PNTS) approach under unreliable CDUs to effectively solve the problem. The results demonstrate that the developed PNTS efficiently solves the industrial case study.

References

AL-AHMARI, A., KAID, H., LI, Z. & DAVIDRAJUH, R. 2020. Strict minimal siphon-based colored Petri net supervisor synthesis for automated manufacturing systems with unreliable resources. *IEEE Access,* 8**,** 22411-22424.

AL-AHMARI, A., KAID, H., LI, Z., WU, N., EL-TAMIMI, A.-A. & QIAO, Y. 2022. A New MINLP Continuous Time Formulation for Scheduling Optimization of Oil Refinery with Unreliable CDUs. *Mathematical Problems in Engineering,* 2022.

AL-SHARRAH, G., ALATIQI, I., ELKAMEL, A. & ALPER, E. 2001. Planning an integrated petrochemical industry with an environmental objective. *Industrial & engineering chemistry research,* 40**,** 2103-2111.

ALHARKAN, I., SALEH, M., GHALEB, M. A., KAID, H., FARHAN, A. & ALMARFADI, A. 2020. Tabu search and particle swarm optimization algorithms for two identical parallel machines scheduling problem with a single server. *Journal of King Saud University-Engineering Sciences,* 32**,** 330-338.

GLOVER, F. 1989. Tabu search—part I. *ORSA Journal on computing,* 1**,** 190-206.

HONKOMP, S., LOMBARDO, S., ROSEN, O. & PEKNY, J. 2000. The curse of reality—why process scheduling optimization problems are difficult in practice. *Computers & Chemical Engineering,* 24**,** 323-328.

JAIKUMAR, R. 1974. An operational optimization procedure for production scheduling. *Computers & Operations Research,* 1**,** 191-200.

KAID, H., AL-AHMARI, A. & LI, Z. 2020. Colored resource-oriented Petri net based ladder diagrams for PLC implementation in reconfigurable manufacturing systems. *IEEE Access,* 8**,** 217573-217591.

KAID, H., AL-AHMARI, A., LI, Z. & AMEEN, W. 2021. Deadlock Control and Fault Detection and Treatment in Reconfigurable Manufacturing Systems Using Colored Resource-Oriented Petri Nets Based on Neural Network. *IEEE Access*.

KAID, H., ALHARKAN, I., GHALEB, A. & GHALEB, M. A. Metaheuristics for identical parallel machines scheduling to minimize mean tardiness. 2015 International Conference on Industrial Engineering and Operations Management (IEOM), 2015. IEEE, 1-6.

MATTFELD, D. C. & BIERWIRTH, C. 2004. An efficient genetic algorithm for job shop scheduling with tardiness objectives. *European Journal of Operational Research,* 155**,** 616-630.

PELHAM, R. & PHARRIS, C. 1996. Refinery operations and control: a future vision. *Hydrocarbon Processing,* 75.

PONNAMBALAM, S., JAWAHAR, N. & ARAVINDAN, P. 1999. A simulated annealing algorithm for job shop scheduling. *Production Planning & Control,* 10**,** 767-777.

SABUNCUOGLU, I. & BAYIZ, M. 1999. Job shop scheduling with beam search. *European Journal of Operational Research,* 118**,** 390-412.

SHOBRYS, D. E. & WHITE, D. C. 2000. Planning, scheduling and control systems: why can they not work together. *Computers & Chemical Engineering,* 24**,** 163-173.

WU, N. 1999. Necessary and sufficient conditions for deadlock-free operation in flexible manufacturing systems using a colored Petri net model. *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on,* 29**,** 192-204.

WU, N., CHU, F., CHU, C. & ZHOU, M. 2008a. Short-term schedulability analysis of crude oil operations in refinery with oil residency time constraint using Petri nets. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews),* 38**,** 765-778.

WU, N., CHU, F., CHU, C. & ZHOU, M. 2008b. Short-term schedulability analysis of multiple distiller crude oil operations in refinery with oil residency time constraint. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews),* 39**,** 1-16.

WU, N., CHU, F., CHU, C. & ZHOU, M. 2009. Hybrid Petri net modeling and schedulability analysis of high fusion point oil transportation under tank grouping strategy for crude oil operations in refinery. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews),* 40**,** 159-175.

WU, N., QIAO, Y., LI, Z., AL-AHMARI, A. M., EL-TAMIMI, A.-A. & KAID, H. 2022. A Novel Control-Theory-Based Approach to Scheduling of High-Throughput Screening System for Enzymatic Assay. *IEEE Transactions on Systems, Man, and Cybernetics: Systems,* 52**,** 7667-7678.

WU, N. & ZHOU, M. 2004. Modeling and deadlock control of automated guided vehicle systems. *Mechatronics, IEEE/ASME Transactions on,* 9**,** 50-57.

WU, N. & ZHOU, M. 2009. *System modeling and control with resource-oriented Petri nets*, CRC Press, Taylor & Francis Group, New York.

WU, N., ZHOU, M. & CHU, F. 2008c. A Petri net-based heuristic algorithm for realizability of target refining schedule for oil refinery. *IEEE Transactions on Automation Science and Engineering,* 5**,** 661-676.

WU, N., ZHOU, M. & LI, Z. 2015. Short-term scheduling of crude-oil operations: Enhancement of crude-oil operations scheduling using a Petri net-based control-theoretic approach. *IEEE Robotics & Automation Magazine,* 22**,** 64-76.

YANG, S. & WANG, D. 2001. A new adaptive neural network and heuristics hybrid approach for job-shop scheduling. *Computers & Operations Research,* 28**,** 955-971.

ZHANG, S., WU, N., LI, Z., QU, T. & LI, C. 2017. Petri net-based approach to short-term scheduling of crude oil operations with less tank requirement. *Information Sciences,* 417**,** 247-261.

Husam Kaid is an assistant professor in the Department of Industrial Engineering, College of Engineering, at Taibah University in Saudi Arabia. In 2021 and 2015, he received his PhD and MS in Industrial Engineering from King Saud University in Saudi Arabia, respectively. In 2010, he received a BS in Industrial Engineering from Taiz University in Yemen. His current research interests include Petri net theory and application, supervisory control of discrete event systems, workflow modeling and analysis, system reconfiguration, simulation, operations research, optimization techniques, product design analysis, and applications of decision support systems in manufacturing.