sciendo

Management Systems in Production Engineering

2023, Volume 31, Issue 3, pp. 263-270

Date of submission of the article to the Editor: 12/2022
Date of acceptance of the article by the Editor: 07/2023

DOI 10.2478/mspe-2023-0029

MODIFIED RESOURCE-CONSTRAINED PROJECT SCHEDULING TO MINIMIZE IDLE TIME FOR BANBURY MIXING PROCESS: A CASE STUDY IN THE TIRE MANUFACTURING INDUSTRY

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Abstract:
The Banbury mixing process (BMP) is to supplies the specific characteristic compounds for the tire manufacturing process. Idle time in the BMP was a problem caused by the aging process between mixing steps and the limited space for processing, measured in pallets. In this study, the resource-constrained project scheduling model (RCPS) is modified in case of the objective function and the input value of resource constraint to minimize idle time (SST). The complete minimization (Cmax) is changed from minimizing the starting time of the last job to the starting time of all jobs. In addition, the non-limited resource is defined as the input for the space capacity to reduce the idle time. As the results, the SST can provide the schedule that make less 5 time periods of idle time. Moreover, when considering the relationship between mixing and aging, aging process that is scheduled from SST starts immediately comparison to Cmax that some of aging process are not. Furthermore, the effect of the quantity of pallets was also examined. Although the non-limited resource does not make any delay to the schedule but the limited quantity is not. When pallets are limited, aging jobs were significantly impacted, with the last aging pallet being delayed. To reduce delays, it prepares an adequate supply of pallets that is close to or equal to its requirement that is defined by the non-limited resource. Further research combining the scheduling of the BMP with the tire manufacturing process and more techniques to modify RCPS are applied.

Key words: *RCPS, natural aging process, idle time, production scheduling, Banbury mixing process*

INTRODUCTION

The tire manufacturing process involves several steps, including mixing the rubber compound, shaping the rubber compound into a tire, curing the tire, and inspecting the finished product. At the step for mixing the rubber compound, a method called the Banbury mixing process is used to mix the rubber compounds by using a machine called a Banbury mixer. The ingredients, such as natural and synthetic rubber, fillers, and additives, are weighed and placed in the mixer, where they are subjected to intense heat and shear forces. The mixing process consists of several stages, including charging, pre-mixing, mixing, cooling, and discharging. After the rubber compound is mixed in the Banbury mixer, the natural aging process is triggered immediately. The natural aging process for a rubber compound in the Banbury mixing process refers to the changes that occur in the rubber compound over time due to the effects of heat, light, and other environmental factors. During natural aging, the physical properties of the rubber compound can change, such as its strength, stiffness, and toughness. These changes can occur due to a variety of mechanisms, such as the formation of free radicals, the migration of plasticizers, and the breakdown of crosslinks.

The Banbury mixing process is an important internal supplier of the tire manufacturing process, as it helps to produce high-quality rubber compounds with good consistency and uniformity. The rubber compound is a critical component of the tire, and the mixing process plays a significant role in determining the final properties of the tire. In the Banbury mixing process of the case study company, those rubber compounds required 1-5 steps of mixing according to their characteristics. Consequently, the natural aging process is also required 1-5 times. Because each natural aging process takes 4 or 8 hours, depending on their characteristics, to age themselves in the natural environment, the problem in the case study company's Banbury mixing process is idle time. Idle time refers to the time during which an employee or a machine is not being used to perform work. Idle time not only represents a waste of non-productive labour in the context of the Banbury mixing process, but it also increases the energy consumption of Banbury mixers. Banbury mixers require energy to increase and keep the temperature over 150 degrees Celsius. Long periods of natural aging and space capacity are the causes of idle time. The natural aging process between each step of compounds could cause some periods of idle time if any slots of processing time (mixing time) are not suitable, as illustrated in Fig. 1.

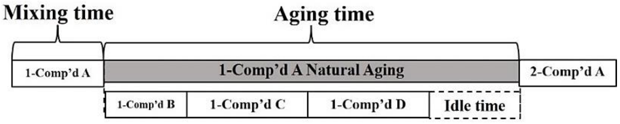


Fig. 1 Idle time from the natural aging process

In addition, space capacity refers to the amount of space that is available or that can be used for a particular purpose. In the context of the Banbury mixing process, the space capacity refers to the quantity of the pallet. The quantity of the pallet is considered in each period of time to ensure that it does not gather more than its capacity. For instance, suppose the quantity of the pallet is 17 pallets; compound A2 requires 8 pallets at that time. The pallet had already used 12 pellets. It means that the job is to create compound A2 delays and a period of idle time, as shown in Fig. 2.

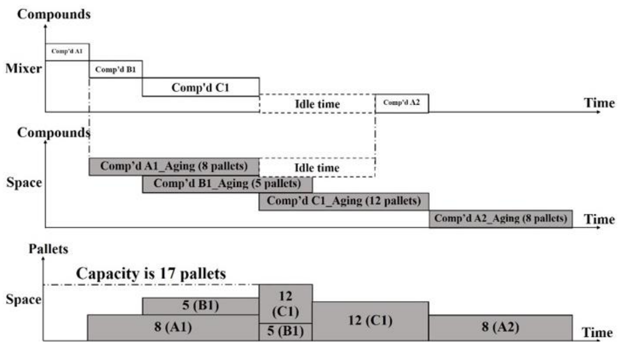


Fig. 2 Idle time from the quantity of the pallet

In this paper, an objective function of the RCPS model is proposed to minimize the idle time, and the complete time is still the same as the project completion time (Cmax). Moreover, the pallets are a renewable resource that can be replenished or regenerated over time. However, to manage the goal of the Banbury mixing process, a strategy is provided to find the difference between a renewable resource with limited amount and non-limited amount of the pallet.

LITERATURE REVIEW

Previous objective functions

Because scheduling in the Banbury mixing process relates to multiple resources, such as the Banbury mixers and the quantity of the pallet, the resource-constrained project scheduling problem (RCPSP) is the first option to be applied. RCPSP is a type of optimization problem that involves scheduling a set of project activities to be completed within a given time frame while also taking into account limited resources (such as materials, labour, and equipment). The goal of the RCPSP is to find a schedule that minimizes the overall duration of the project or the cost of completing the project, while also satisfying the resource constraints. The RCPSP is identified as determining the time required to implement the activities of a project to achieve a certain objective [1, 2]. In RCPSP, the objective function is a mathematical expression that represents the purpose of the scheduling procedure. The exact problem being solved and the project's goals will determine the precise form of the objective function. The most popular type of objective function for the RCPSP is the time-based objective function that is involved completion time and delay time [3].

- The project completion time or makespan (M) is defined as the time when all jobs associated with a project are fully executed [4, 5, 6].
- The performance time minimization (APT) is equivalent to the makespan minimization. This situation does not happen in a multi-project environment where the makespan is defined as the maximum makespan among all projects and the average performance time as the average performance times of all projects [7, 8].
- Weights are used to minimize the weighted makespan (WM) where the makespan value is multiplied by the corresponding weight, so the higher the weight, the greater the influence on the objective function [9, 10].
- The average project delay minimization (APD) is to consider that the number of projects is a parameter of the problem. The objective functions based on the total delays are classified as average project delay [11, 12].
- The standard deviation mean lateness minimization (SDML) is to balance the delays incurred in each project [13, 14].
- The average project earliness minimization (APE) is to consider that the early completion sometimes negatively influences the project delivery, so it can also be penalized with the same or a different value used for delays. [7].
- Other measures based on delays and efficiency of the generated schedules were studied under average percent project delay, efficiency, and robustness. In this review, the measures related to efficiency, either in average or total values, are classified as the minimization of the average percent project delay (APPD) [15, 16], the maximization of robustness (R) [16, 17], and the weighted project delay minimization (WPD) [18, 19].

However, these objective functions of the RCPS model do not concern on idle time. The scheduling results from those objective functions do not try to reduce the idle time ratio.

Previous resource constraints

Furthermore, the space capacity is demonstrated by the parameter of the resource constraint. This constraint is a limitation on the availability or use of a particular resource. It could refer to a variety of different types of resources, including physical resources like machines or space. Resource constraints can impact a manufacturer's ability to achieve their goals or objectives, and they may need to be managed or addressed in order to move forward. Some common strategies for managing resource constraints include prioritization, delegation, and optimization. Most papers on scheduling problems have used resource constraints to accomplish their goals.

- Renewable resources (R) present a fixed existence that is renewed in each time period [20, 21, 22].
- Non-renewable (NR) arise from the need to optimize resources that present a unique existence for the entire time horizon so that once they are assigned to a job, they are not renewed [23, 24, 25].
- Resource rent (RR) is to the restricted existence of renewable resources that can cause timeouts for a job execution start, generating delays in a project completion and costs for delays [26, 27].
- Uncertainty in resource existence (RU) moves the problem to a stochastic area especially in large production processes [28, 29].
- The existence of partially renewable resources (PRR) is to renew the resources in a set period of time [29].
- Resource unavailability planning (RUP) provides flexibility to the resource availability, keeping the problem in a deterministic environment [30].
- Capacity limitations (CL) is the unavailability planning that refers to periods where there is no specific resource [31].

However, the pallet is the resource that can be prepared sufficiently. The quantity of pallet can be the condition of requirement instead of the existing as presented in these resource constraints.

METHODOLOGY OF RESEARCH

Proposed objective function

The shortest project completion time, also known as Cmax, is a common objective function used in project scheduling problems. The goal of the Cmax objective is to minimize the overall duration of the project, that is, to find a schedule that completes the project in the shortest possible time. In the context of project scheduling, Cmax is typically defined as the length of the longest path from the start of the project to the completion of the final activity. This is often referred to as the "critical path" of the project. The mathematical expression to find the Cmax is to minimize the following equation:

$$C_{max} = \sum_{t=1}^{NT} x_{NJt} \times t \quad (1)$$

As Equation (1), the starting time of the last job (x_{NJt}) is multiplied by time period (t). When one of (x_{NJt}) is 1 and others is 0, Cmax will be defined. For example, if the starting time of the last job (*NJ*) at time period 100 (x_{NJ100})) is equal to 1, the Cmax will be equal to 100.

However, the shortest complete time is not only the goal of the Banbury mixing process but also the lowest idle time. Idle time minimization is the goal of minimizing the amount of time that resources are idle or not being used. To minimize idle time, the objective function for project completion time minimization is developed from concerning the starting time of the last job (x_{NJt}) to concerning the starting time of all jobs ($x_{j,t}$) as shown in Fig. 3.

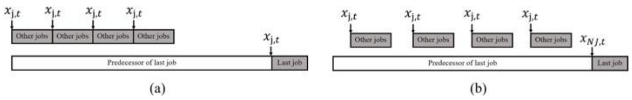


Fig. 3 Objective definition (a) Cmax, (b) SST

The objective function is changed to the mathematical expression which is to minimize the following equation.

$$SST = \sum_{t=1}^{NT} \sum_{j=1}^{NJ} x_{jt} \times t \quad (2)$$

As Equation (2), the starting time of all job ($x_{j,t}$) is multiplied by time period (t). When one of ($x_{j,t}$) of each job is 1 and the other is 0, the sum of starting time (SST) will be defined. For example, if the starting times of job 1, job 2 and job 3 are 0, 10 and 100, respectively, the SST will be equal to 110.

A non-limited resource definition

Normally, the quantities of resources in the RCPS model are defined as the integer values. However, the specific values of the resource constraint can some effects on the schedules and the runtime of the optimization process. To solve these issues, The quantity of the pallet (c_4) is defined to the non-limited resource. A non-limited resource is a resource that is not subject to any constraints or limitations on its availability or use. In other words, a non-limited resource is one that can be used freely without any restrictions. These types of resources are often considered to be unlimited or infinite because they cannot be depleted or exhausted through use. Non-limited resources can be used to achieve a wide range of goals and objectives without the constraints that limited resources may impose. The non-limited resource can be defined by the sum of the usage of all jobs at that resource as the following equation.

non-limited value of resource $r = \sum_{j=1}^{Nj} U_{jr}$

This equation is to find the non-limited value of the capacity of resource *r* by summing all of the requirements of all jobs j that need to use resource *r*. The jobs of the aging process in the context of the Banbury mixing process require quantities of the pallet to place the rubber compounds and the aging process itself. With this value, operators can know and prepare the quantity of the resource to be sufficient to meet the non-limited value, which in this case is the quantity of the pallet. It means that the strategy is changed from preparing the pallet as its capacity to preparing the pallet as its all requirements instead.

Mathematical model

The RCPSP involves finding a feasible scheduling of a set of jobs that satisfies resource and precedence constraints while minimizing the overall duration of the project or the cost of completing the project. To do this, the RCPSP must consider the processing time of each job, the dependencies between jobs (as determined by the successor jobs), and the availability and usage of different resources. The objective of the RCPSP is to find a schedule that meets all of these constraints and achieves the desired optimization goal.

The RCPSP is classified as a combinatorial optimization problem because it involves finding a combination of decisions that optimizes a particular objective. In this case, the decisions relate to the scheduling of the jobs and the use of resources, and the objective is to minimize the overall duration of the project or the cost of completing the project. Combinatorial optimization problems can be challenging to solve because they often involve a large number of variables and constraints, and finding the optimal solution may require considering a large number of possible combinations. The following assumptions for RCPSP have been made in the study including:

- The processing times for the jobs are known and fixed.
- Each job has a set of successor jobs.
- All job needs to be assigned.
- The limitation of time can be estimated by the sum of the duration of all jobs.
- Banbury mixers are renewable at each time period.
- The batch sizes are equal to order sizes and batch splitting is not permitted.
- Batches are available for processing at time zero.
- A slot of processing times includes mixing time, setup time, and time between batch.
- Worker resource is not concerned.
- The jobs must be scheduled non-preemptively. The processing of the jobs cannot be interrupted after it starts.
- The quantity of the pallet can be defined into two types including the non-limited quantity of the pallet which can be calculated by the sum of the usage of all jobs at resource 4 and the limited quantity of the pallet which can be defined as the company data.
- The odd number is the job of mixing process and the even number is the job of aging process.

Indices:

J = Set of Job [1, 2, 3, …, *NJ*]

T = Set of Time [0, 1, 2, 3, ..., *NT*]

R = Set of Resource [1, 2, 3, ..., *NR*]

S = Set of Predecessor [[1, 2], [1, 3], ...]

Parameters:

p_j = Processing time of job *j* (unit: time period)

U_{jr} = Used resource *r* for job *j* (unit: machine, pallets)

c_r = Capacity of resource *r* (unit: machine, pallets)

Decision variables:

x_{jt} = Starting time *t* assigned for job *j*

Objective Function:

$Z_{min} = SST$

Subject to:

$$SST = \sum_{t=1}^{NT}\sum_{j=1}^{NJ} x_{jt} \times t$$

$$c_4 = \sum_{j=1}^{Nj} U_4$$

$$\sum_{j=1}^{NJ}\sum_{t'=\max(0,t-p_j+1)}^{t+1} U_{jr} \times x_{jt'} \leq c_r \quad \forall r \in R, t \in T$$

$$\sum_{t=0}^{NT} x_{jt} = 1 \quad \forall j \in J$$

$$\sum_{t=0}^{NT}(t \times x_{st}) - (t \times x_{jt}) \geq p_j \quad \forall j,s \in S$$

$$x_{jt} = 0 \text{ or } 1, \quad \forall j \in J, \quad t \in T$$

The objective function is to minimize the sum of the starting time *t* assigned for job *j*. Constraint 1 is to find the sum of the starting time *t* assigned for job *j*. Constraint 2 is the resource constraint, which limits the number of resource usage at a specific range of time periods as *t′* = max (0, *t*-p_j+1). Constraint 3 is to set the capacity if the resource 4 equal to its requirement. Constraint 4 is the assignment constraint, which is to assign the beginning time t assigned for job *j* at least once. Constraint 5 is the predecessor constraint, which is to set the order between the job and the preceding job. Constraint 6 is the binary constraint = 1, if job *j* is assigned to begin at time *t*; otherwise, = 0.

RESULTS OF RESEARCH

The idle time of the Banbury mixing process can be affected by factors, including the aging time of the materials being mixed and the availability of resources such as mixers and pallet. In the result, the real data from the case study company is applied to two subsections. The first subsection is to compare the schedule from the results between the objective functions of Cmax and SST. The second subsection is to compare the schedule based on two assumptions, including the non-limited and the limited quantity of the pallet. The modified RCPS model of both experiments is formulated in Python 3.9 and solved by the MIP library (COIN-OR Branch-and-Cut solver, CBC), which is performed on a personal computer with an Intel Core i7 2.80 GHz CPU and 8 GB RAM. All of the information is described as follows.

There are 64 jobs including 31 jobs for mixing, 31 jobs for aging, 1 job for the start node (job 0) and 1 job for the finish node (job 63). The 3 resources (r = 1, 2, 3 and 4 are represented Special BB, Non-pro BB, Pro BB and the amount of the pallet, respectively). Capacity (c_r) of all mixer types are amounts of resource 1, 2 and 3 equals to 1 mixer and resource 4 equal to 50 pallets for the company data or 244 pallets for the sum of all pallet consumption requirements. The information of processing time, resource usage and predecessors are shown in Table 1.

Table 1

Information for real problem

Jobs (*i*)	P_j	U_{jr}				Predecessors
		1	2	3	4	
1	11	1	0	0	0	0
2	20	0	0	0	17	1
3	4	1	0	0	0	30
4	20	0	0	0	5	3
5	10	1	0	0	0	32
6	20	0	0	0	13	5
7	8	1	0	0	0	0
8	20	0	0	0	12	7
9	3	0	0	1	0	0
10	20	0	0	0	6	9
11	3	0	0	1	0	0
12	20	0	0	0	5	11
13	9	0	0	1	0	34
14	20	0	0	0	21	13

Table 1 Continued
Information for real problem

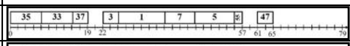
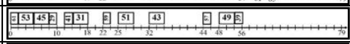
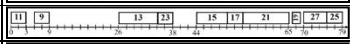
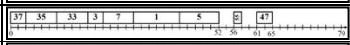
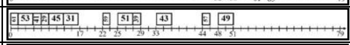
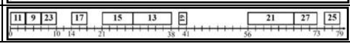
15	8	0	0	1	0	36
16	20	0	0	0	18	15
17	3	0	0	1	0	38
18	20	0	0	0	7	17
19	2	0	0	1	0	40
20	20	0	0	0	1	19
21	11	0	0	1	0	44
22	20	0	0	0	23	21
23	4	0	0	1	0	0
24	20	0	0	0	13	23
25	5	0	0	1	0	48
26	20	0	0	0	8	25
27	5	0	0	1	0	104
28	20	0	0	0	8	27
29	2	0	1	0	0	0
30	10	0	0	0	2	29
31	4	0	1	0	0	0
32	20	0	0	0	5	31
33	8	1	0	0	0	0
34	10	0	0	0	12	33
35	7	1	0	0	0	0
36	10	0	0	0	11	35
37	4	1	0	0	0	0
38	10	0	0	0	6	37
39	1	0	1	0	0	42
40	10	0	0	0	1	39
41	2	0	1	0	0	0
42	20	0	0	0	1	41
43	3	0	1	0	0	46
44	20	0	0	0	6	43
45	4	0	1	0	0	0
46	20	0	0	0	7	45
47	4	1	0	0	0	50
48	10	0	0	0	6	47
49	3	0	1	0	0	52
50	10	0	0	0	5	49
51	3	0	1	0	0	54
52	20	0	0	0	5	51
53	3	0	1	0	0	0
54	20	0	0	0	7	53
55	2	1	0	0	0	58
56	10	0	0	0	3	55
57	2	0	1	0	0	60
58	10	0	0	0	3	57
59	2	0	1	0	0	62
60	20	0	0	0	3	59
61	2	0	1	0	0	0
62	20	0	0	0	4	61

Objective function comparison

This subsection compares the time when the mixers need to heat up to over 150°C between two objective functions, including project complete time minimization (Cmax) and idle time minimization (SST). The available time (Avail) is the time that mixers need to stand by for the mixing process. Mixing time (MT) is the time when the compounds are mixed in the mixer, and idle time (Idle) is the time when the mixers stand by but are not mixing any compounds. In addition, the relationship between mixing and the aging process is also compared. In this case, the starting time of the aging process and the finish time of the mixing process should be the same. With Python 3.9 and the MIP library executing 64 jobs on 3 types of Banbury mixer and 244 pallets, the RCPS-Cmax model took 524.95 seconds of runtime to be optimized. The objective value is 100, which means the stating time of the last job (finish node). On the other hand, the RCPS-SST model can take only 11.58 seconds of runtime to be optimized. The objective value is 2,298, which means the sum of the stating times of the all jobs.

With both schedules, the bottleneck machine is MC1, which can be defined by the highest time of machine runtime, and the longest path of jobs is 0-53-54-51-52-49-50-47-48-25, which defines the last job at MC3. The starting time of the jobs at MC2 is not fixed by the bottleneck machine, and the longest path can be more than one point in time period. As shown in Table 2, the mixing time (MT) of both schedules is 31 time periods, but the available times are not. The schedule from Cmax requires MC2 to stand by 56 time periods of available time, which is higher than the schedule from SST's 5 time periods. Moreover, the schedule from Cmax is not appropriate in the case of the Banbury mixing process, since the aging process should start after the mixing process has finished immediately.

Table 2
Schedule results from Cmax and SST

Obj	MC	Schedules	Avail	MT	Idle
Cmax	1		65	58	7
	2		56	31	25
	3		79	52	27
SST	1		65	58	7
	2		51	31	20
	3		79	52	27

As Table 3, the four pairs of jobs include 63-64, 35-36, 67-68 and 39-40 which finish time (FT) of mixing is not equal to starting time (ST) of aging. Consequently, changing the optimization objective from complete time minimization (Cmax) to idle time minimization (SST) have a significant impact on the schedule and the allocation of resources.

Table 3
Finish time of mixing and starting time of aging

Job types		SST			Cmax		
Mix	Age	ST of Mix	FT of Mix	ST of Age	ST of Mix	FT of Mix	ST of Age
109	110	0	2	2	0	2	2
97	98	2	5	5	2	5	5
63	64	5	7	7	12	14	15
35	36	7	9	9	9	11	12
67	68	9	13	13	5	9	10
39	40	13	17	17	14	18	21
107	108	22	24	24	22	24	24
95	96	25	28	28	25	28	28
61	62	28	29	29	55	56	56
65	66	33	36	36	32	35	35
105	106	44	46	46	44	46	46
93	94	48	51	51	48	51	51

Minimizing complete time refers to the goal of minimizing the total duration of the project, from start to finish. This objective is often used when the goal is to complete the last job as quickly as possible. On the other hand, minimizing idle time refers to the goal of minimizing the gap between jobs. This objective is used when the goal is to start the jobs as soon as possible. If there are concerns idle time and the relationship between mixing and aging processes, SST will provide a better schedule.

Effect of the quantity of the pallet

A non-limited quantity of the pallet is a situation in which there is an unlimited supply of pallets available for use. This occur if the pallets are sufficient to meet the requirements for them. In case of the RCPS, the non-limited quantity of the pallet would not be a constraint on the project or process in which they are being used. The schedule can proceed without having to worry about running out of pallets or having to allocate resources to acquire more pallets. It is worth noting that even in a situation with a non-limited quantity of the pallet, there may still be other resources that are limited or constrained, such as mixers. These limited resources could still affect the efficiency and performance of the project or process, and they would need to be carefully managed and allocated.

From the previous section, the result of the RCPS-SST model based on the assumption of the unlimited quantity of the pallet is already provided. This subsection illustrates the effect of the quantity of the pallet on the schedule result provided by the RCPS-SST model. The value of capacity of resource 4 can be the defined value and the sum of the usage of all jobs at resource 4. These two quantities of the pallet can provide different schedules in case the quantity of the pallet reaches its limit and the starting time needs to be postponed. Consequently, this section will provide the result of the limited quantity of the pallet as 50 pallets. With Python 3.9 and the MIP library, this assumption takes 28,842.23 seconds of runtime to provide a feasible solution. The objective value of the feasible solution is 2,538 which means the sum of the stating times of all jobs that some jobs are postponed by the quantity of the pallet.

With the non-limited quantity of the pallet, the last aging pallet can finish at time period 100. The highest quantity of usage is 88 pallets at time period 42 as shown in Fig. 4(a).

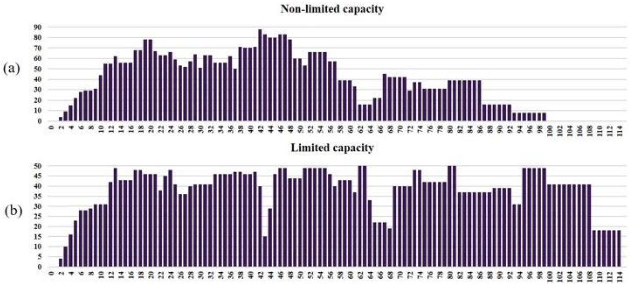


Fig. 4 Amount of the pallet usage; (a) non-limited; (b) limited

This means if the current pallet quantity is 88 pallets, the delay will not happen. However, the current pallet quantity is 50 pallets. In the case of the mixing jobs, although, some of the mixing jobs are delayed in comparison to the non-limited pallet, they are not delayed at all. The mixer can stand by for the same quantity of time as the non-limited pallet. There is just a change in the position of idle time, but the value of total idle time is still the same. Furthermore, in the case of aging jobs, the last aging pallet is delayed to time period 114. The quantities of usage reach 50 pallets at time period 62, 63, 80 and 81 as shown in Fig. 4(b).

Consequently, it can imply that the quantities of the pallet are required for each job in the project schedule. The effect of the quantity of the pallet in this paper depends on how the resources are being used and the specific constraints and requirements of the project. If the quantity of the pallet is relatively high for certain jobs, it will affect the overall efficiency of the project schedule. This is because the use of large quantities of the pallet for certain jobs might result in idle time or delays for other jobs that are waiting for those pallets to become available. Preparing the quantity of the pallet equal or close to 244 pallets is the better way to reduce the delay of the complete time.

DISCUSSION AND CONCLUSION

The Banbury mixing process at the case study company involves mixing and aging process. The problem identified in the Banbury mixing process at the case study company is idle time, which can result in unnecessary energy consumption. The causes of idle time in the Banbury mixing process at the case study company are identified as the aging process between mixing steps and the availability of space (measured in pallets) for processing the compounds. The aging process can result in idle time if there are gaps in the processing schedule, while space limitations can cause delays in production and result in idle time if the available space is already being used to capacity. To find the solutions, this case study compared the use of two objective functions, project complete time minimization (Cmax) and idle time minimization (SST), in the scheduling results based on the real data of Banbury mixing process. The RCPS-SST model, which minimizes idle time, took less 5 time periods and resulted in a schedule with a shorter idle time for the non-bottleneck machine. Additionally, the schedule from Cmax was not suitable for the Banbury mixing process because it did not align the finish time of mixing with the start time of aging for certain pairs of jobs. In contrast, the schedule from SST did align the finish time of mixing with the start time of aging for all pairs of jobs. Therefore, minimizing idle time (SST) provides a better schedule in this case, particularly if there are concerns about idle time and the relationship between mixing and aging processes. Furthermore, this case study also examined the effect of the quantity of pallets on the schedule of the Banbury mixing process. The results showed that having a limited quantity of pallets, where there is a finite supply of pallets and they may run out, can impact the efficiency of the schedule. When the quantity of pallets is limited some mixing jobs in the non-bottleneck machine are delayed, but the total idle time remains the same. In contrast, the aging jobs are significantly impacted, with the last aging pallet being delayed from time period 100 to 114. This shows that the quantity of pallets can be a critical factor in the efficiency of the Banbury mixing process, and it is important to ensure that there is an adequate supply of pallets available to meet the needs of the process. To reduce delays and optimize the schedule, it may be beneficial to prepare a quantity of pallets that is equal to or close to its requirement.

Further research could involve combining the scheduling of the Banbury mixing process with the tire manufacturing process and exploring additional techniques for modifying the RCPS model in order to optimise efficiency and minimize idle time. This could potentially lead to significant improvements in the production process and overall efficiency of the tire manufacturing industry. By combining the scheduling of the Banbury mixing process with the tire manufacturing process, researchers can gain a more holistic understanding of the production process and identify opportunities for optimization. This could involve looking at the interdependencies between different stages of the process and finding ways to minimize bottlenecks and delays. Additionally, by applying more techniques to modify the RCPS model, researchers can continue to improve the scheduling model and make it more effective at minimizing idle time and maximizing efficiency. Overall, this kind of research could have a significant impact on the tire manufacturing industry by improving efficiency and reducing costs.

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