A Simulation based Optimization Study for Optimum Sequencing of Precast Components Considering Supply Chain Risks

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Abstract: Unquestionably, Precast Supply Chain (PSC) abounds with many risks distributed along its echelons. Despite that there is a wide consensus among the previous studies about the negative impact of these risks on the PSC performance, its effect on making operational decisions in precast plants such as scheduling of Precast Components (PCs) is still ambiguous. So, this study aims at exploring and quantifying the effect of considering PSC risks on the optimum PCs sequences. To accomplish this, different processes of the PSC with their associated risks are modelled via a discrete event simulation model. Then, the developed simulation model is linked with an optimizer to generate PCs sequences that achieve on-time delivery of PCs with minimum production costs. This optimization process is conducted twice, with and without considering supply chain risks. Interestingly, the optimum PCs sequences generated in both cases are totally different. More importantly, the optimized PCs sequences produced without considering risks may backfire and cause higher production and penalty costs if they are applied to a PSC exposed to risk. So, investing in making a reliable risk management plan of the PSC not only can cushion the risks impact but also can lead to better sequences of PCs.

1 INTRODUCTION

By virtue of their benefits, construction by using precast components is adopted increasingly all over the world (Sacks et al., 2004). Moreover, this construction method is fostered to be adopted in the near future not only in public housing but also in infrastructure projects by many countries (Wang et al., 2018a). Owing to the fact that the precast construction method is an integration between construction and manufacturing domains (Wang et al., 2018b), risks are divided between the construction site and the precast plant, where production managers shoulder delivery of Precast Components (PCs) according to contracted due dates so as not to cause delay in installation of PCs at construction sites. To accomplish this target, pre-caster makes some operational decisions such as resource allocation, inventory management and sequencing of required PCs. However, there are risks embedded in the different echelons of the Precast Supply Chain (PSC) starting from material supplying and followed by production, transportation and approval of PCs at construction site (Wang et al., 2018b). The PSC is a unique multi-echelon supply chain that is different from other supply chains because the precast production alters between push (repetitive production) and pull (on-time delivery to construction sites) production all the time. This makes the PSC more susceptible to risks which cause more costly supply chain and handicap on-time delivery of PCs, and as a result the advantages of using the precast construction method can be easily wiped away (Wang et al., 2018b). So, there exists a need to understand how PSC risks can influence the operational decisions of the pre-casters. Sequencing of PCs is one of the most important operational decisions in precast plants. It aims at ordering different types of PCs on a number of sequential operations in order to meet the contracted due dates, and meanwhile reducing production costs. To date, literature is riddled with studies on sequencing of PCs; diverse issues had been addressed in these studies such as mold planning and leveling (Hu, 2007), available space between

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production processes (Ko and Wang, 2011), multiple production lines (Yang et al., 2016), incorporating of mold manufacturing, storage and transportation processes (Wang and Hu, 2017), demand fluctuations of PCs (Wang and Hu, 2018) and considering stochastic processing times (Wang et al., 2018a). On the other hand, literature lacks studies that investigate how multiple risks can impact the performance of the PSC, which aims at on-time delivery of PCs with the required quality at lowest cost incurred by supply chain members (Tuncel and Alpan, 2010). (Wang et al., 2018b) was the pioneer in meeting this need by using discrete event simulation to evaluate the performance of the PSC under multiple risks from pre-casters' perspective. Their conclusions illuminated pre-casters to the criticality of each risk embedded in different stages of the PSC. Despite this, the question of whether considering risks in the PSC can affect operational decisions such as PCs sequencing, is yet to be answered. So, this study is intended to provide numerical justification of the value of considering the PSC's risks in determination of optimum PCs sequences in precast plants. This is done by using a simulation optimization approach to compare between the optimum PCs sequences generated with and without considering risks in the PSC. But before applying this approach, different risks propagated through echelons of the PSC are identified and assessed by using information from literature. These risks are then incorporated into different operations of the PSC in a discrete event simulation model. Thereafter, this simulation model is integrated with an optimization package to search for the optimum PCs sequence which minimizes both penalty and production costs.

The reamaining parts of this paper are organized as follows. Section 2 is the literature review. Section 3 discusses the integration between the risk managemnt and the PSC. The DES model of the PSC is explained in Section 4. The developed simulation-based optimization approach is illustrated in section 5. Results of the study are presented and discussed in section 6. Finally, conclusions are drawn in section 7.

2 LITERATURE REVEW

Due to the fact that the production stage of PCs is at the core of the PSC, many researchers addressed the precast production planning by using either mathematical modeling or Discrete Event Simulation (DES). Regarding using mathematical modeling, (Chan and Hu, 2001) was the first to indicate that the precast production system resembled the traditional flow shop sequencing problem where *n* jobs have to be processed in the same sequence on all *m* machines, and the objective is to minimize the makespan using the appropriate order for these jobs. Despite that literature is full of studies on flow shop sequencing (Yenisey and Yagmahan, 2014), these studies cannot be applied directly to the precast industry because of the specific nature of precast production. So, (Chan and Hu, 2001) formulated a tailored flow shop sequencing model for precast production by considering the realistic nature of the precast production activities. They classified these activities into preemptive or non-preemptive activities and sequential or parallel activities. Their objective was to minimize Tardiness and Earliness (T&E) penalty costs or reduce makespan. More and more scholars enhanced the model proposed by (Chan and Hu, 2001) by incorporating more factors. For instance, (Ko and Wang, 2011) considered the waiting times due to restricted buffer size between production processes. To be closer to the realistic precast production environment, (Yang et al., 2016) enhanced the previous model to consider multiple production lines as well as additional types of production resources such as pallets and curing machine. Despite these improvements, (Wang and Hu, 2017) contended that addressing the precast production problem in isolation from its supply chain would not inevitably lead to on-time delivery of precast components, and hence they added three processes to the precast flow shop sequencing model. One of them is mold manufacturing prior to production processes, and the others are storage and transportation to the construction sites, after production processes. Recently, (Wang and Hu, 2018) extended their model used in (Wang and Hu, 2017) to address demand variability issue by assignment of PCs to proper production line and reordering of PCs. Interestingly, genetic algorithms were a common method used in the previous studies by virtue of its performance to tackle such nondeterministic polynomial (NP)-hard problems.

However, academics often resort to simulation modeling due to its superiority over mathematical modeling to imitate complex stochastic systems (Law, 2007), such as the PSC. To support this, (Wang et al., 2018a) claimed to be the first to consider stochastic processing times within PSC by using simulation modeling to evaluate pre-optimized PCs sequences generated in advance from mathematical optimization. Moreover, (Wang et al., 2018b) developed a DES model to evaluate multiple risks in PSC. Their model was used to prioritize risks under study based on their impact on economic and tech-

Table 1: Identified risks in PSC with its probability and impact, (Michalska and Mazurkiewicz 2011) and (Wang et al., 2018b).

Echelons of PSC	Identified risks	Probability	Impact (hours)	Risk response
Material supplying	Low quality of materials	22%	EXPO(15)	Reordering materials
Precast plant	Machine breakdown	28%	EXPO(50)	Machine repairing
Logistics	Truck failure	EXPO (1000) hrs*	Norm(2,0.71)	Truck repairing
On-site checking	Imperfections in delivered PCs	27%	EXPO(15)	PC repairing
	Rejection of PCs after repairing	19%	Deduced from simulation model	Reproduction of rejected PCs

* Time between failures obeys exponential distribution.

nical factors. After reviewing the aforementioned studies, it is noticed that researchers had not, as yet, addressed precast flow shop sequencing problem while considering multiple risks identified in the PSC. In this work, a DES model is developed to study the different stages of the PSC while considering the associated risks. The simulation environment is used to identify the optimum PCs sequences with considering several real aspects such as the uncertainty of PCs processing times and different operational risks in the PSC. This simulation optimization approach is conducted twice, with and without considering risks in the PSC, and the optimum PCs sequences generated in the two cases are compared and analysed to study the effect of considering PSC risks on the developed optimum precast production schedules.

3 PRECAST SUUPLY CHAIN MANAGEMENT WITH RISK CONSIDERATIONS

This section aims at applying the risk management procedure to the PSC management. But firstly, the definition of PSC management should be clarified.

PSC management can be defined as the applied techniques to link between suppliers, manufacturers, transporters and contractors, so as to deliver PCs on time with required quality and quantity, in a way to reduce system costs incurred by the supply chain members, (Simchi-Levi et al., 2000). However, (Tuncel and Alpan, 2010) argued that overlooking of disturbances across any supply chain can impact its performance. Owing to this fact, contractors are used to procure raw materials as early as possible in traditional construction projects in order to mitigate the consequences of supply chain uncertainties. Unfortunately, the large sizes and heavy weights of PCs hamper stacking them on construction sites surrounded by urban areas, (Wang et al., 2018a). So, integrating risk management with supply chain management is of utmost importance for optimal PSC management. To accomplish this integration, risks pertained to the different parts in the PSC should be firstly identified. Risk identification is an iterative process that needs collaboration between different stakeholders of the PSC. Documentation review is one of many methods that can be used to accomplish this process (Guide, 2001). After determination of different risks that might impact the PSC, assessing the identified risks is the second step in the risk management procedure (Guide, 2001). During this stage, many techniques can be used to assess numerically the likelihood and impact of the identified risks. Despite that there are many risks associated with the different echelons of the PSC, as documented by (Pheng and Chuan, 2001), no much information about their probability and impact is available in literature. Hence, only five main risks in the PSC are considered and summarized in Table 1. It is worth mentioning that the impact of these risks is represented by the time delay they may impose on the system. After risk identification and risk assessment, the third process in the risk management procedure is the risk response, where the risk management team tries to reduce the probability and impact of each risk by using different techniques such as risk aviodance, risk mitigation, risk transfer and risk acceptance. The risk responses mentioned in Table 1 are classified as risk acceptance where there are no other suitable risk responses available for the team to deal with such risks. To sum up, Table 1 represents the output from applying the risk identification, risk assessment and risk response processes to the PSC. This table identified five risks which are poor-quality materials, machine breakdown, truck failure, poor-quality PCs and rejection of PCs at the construction site. These

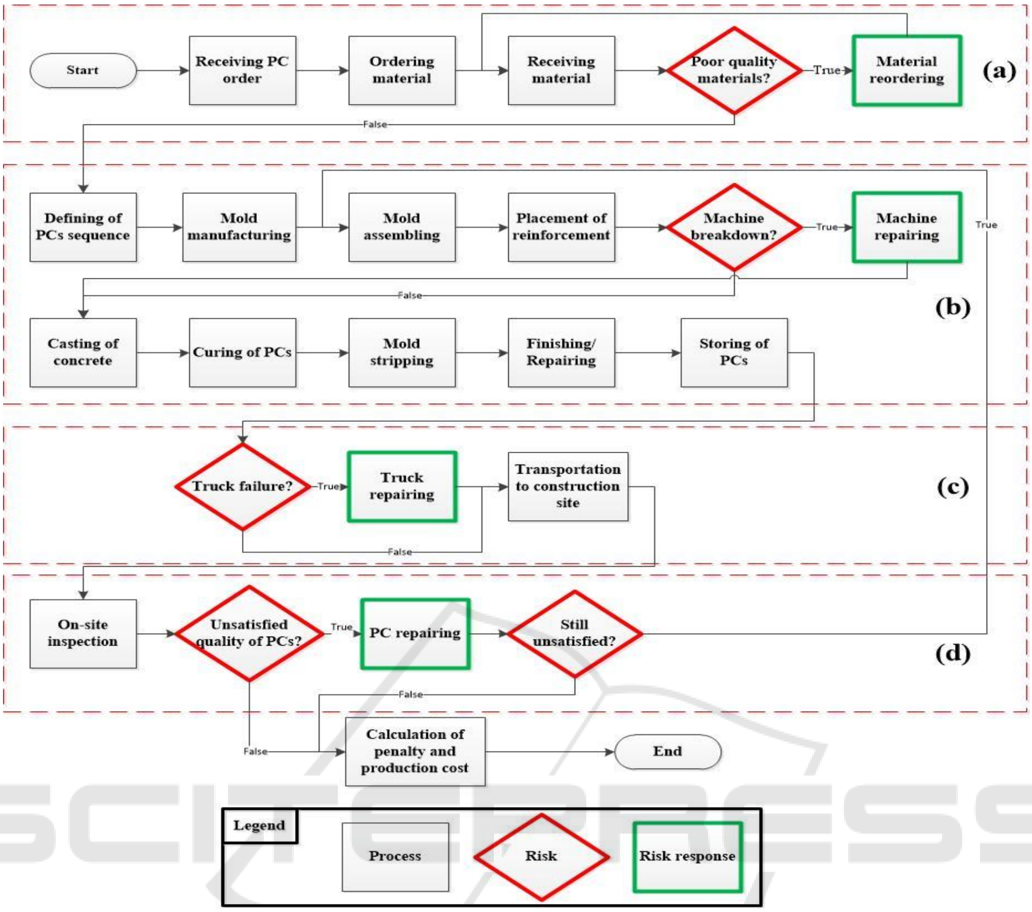

Figure 1: Schematic of PSC with multiple risks in its echelons; (a) Material supplying, (b) Precast plant, (c) Logistics and (d) On-site checking.

risks disrupt different echelons of the PSC which are material supplying, PC production, logistics and on-site checking. These five risks and different operations of the PSC will be incorporated in a developed simulation model, as will be illustrated in the next section.

4 DEVELOPMENT OF SIMULATION MODEL

In this section, a DES model is developed to represent the operations at different echelons of the PSC and its embedded risks aforementioned in Table 1. The developed model considers the whole supply chain of the PCs starting from processes of material supplying to PC inspection on-site with their related risks, as discussed in the previous section. Figure 1 shows the different processes at each echelon of the PSC with their corresponding risks, starting from material-supplying stage and ending with on-site checking of delivered PCs. During the supplying stage, PCs orders are registered and raw materials are solicited. After arrival of the materials, if the precast plant rejects the delivered materials due to their poor quality, the production of PCs will be delayed until inventory is replenished with another shipment of good-quality materials. After that, the production process can start with the identified PCs sequence. The production process begins with mold manufacturing, followed by mold preparation and reinforcement setting. But before proceeding to the casting and curing processes, there is a probability that the machines used in these processes break down, and as a result, the repairing activities will halt the production process. After casting and curing processes, PCs are extracted from molds, finished and stored at the stockyard of the precast plant. The third stage in the PSC is logistics, where the PCs are carried

Table 2: Processing times (hours) of the production and transportation processes in the PSC, and the due date (hours) associated with each PC type.

PC type	Processing times of production and transportation processes (triangular distribution (Min, Mode, Max))									Due date
	M1	M2	M3	M4	M5	M6	M7	M8	M9	
1	(10.2,11,11.5)	(1.3,1.5,1.7)	(1.2,2,2.5)	(0.3,0.5,0.7)	8	(0.8,1,1.2)	(0.3,0.5,0.7)	10	(1.2,1.5,1.6)	164
2	(10,11,11.8)	(0.8,1,1.2)	(1.8,2,2.5)	(0.2,0.4,0.6)	8	(0.8,1,1.2)	(0.3,0.5,0.8)	10	(1.2,1.5,1.6)	140
3	(9,10,10.5)	(0.8,1,1.2)	(1,1.5,1.8)	(0.3,0.5,0.7)	8	(0.3,0.5,0.7)	(0.3,0.5,0.7)	10	(0.8,1,1.2)	164
4	(7.8,8,8.2)	(0.2,0.5,0.8)	(0.8,1,1.2)	(0.1,0.3,0.5)	8	(0.1,0.3,0.5)	(0.3,0.5,0.7)	10	(1.2,1.5,1.6)	160
5	(3.8,4,4.5)	(0.5,1,1.2)	(0.6,0.8,1)	(0.5,1,1.2)	8	(1.2,1.5,1.7)	(0.3,0.5,0.7)	10	(1.2,1.5,1.6)	160
6	(7.5,8,8.5)	(0.3,0.5,0.7)	(1.5,2,2.2)	(0.2,0.4,0.6)	8	(0.3,0.5,0.7)	(0.3,0.5,0.7)	10	(1.2,1.5,1.6)	164
7	(4,5,5.8)	(1.3,1.5,1.7)	(1.5,2,2.2)	(0.2,0.5,0.6)	8	(0.5,1,1.2)	(0.2,0.4,0.6)	10	(0.3,0.5,0.7)	140
8	(4.8,5,5.5)	(0.3,0.5,0.7)	(1.8,2,2.5)	(0.1,0.3,0.5)	8	(0.4,0.6,0.8)	(0.2,0.3,0.5)	10	(1.2,1.5,1.6)	164
9	(7.5,8,8.2)	(1.3,1.5,1.7)	(1.6,1.8,2)	(1,1.2,1.8)	8	(1,1.5,1.8)	(1.2,1.5,1.6)	10	(0.8,1,1.2)	140
10	(3.8,4,4.5)	(0.2,0.4,0.8)	(0.2,0.5,0.7)	(0.4,0.6,0.8)	8	(0.3,0.5,0.7)	(0.2,0.5,0.7)	10	(1.5,2,2.2)	164

M1= mold manufacturing; M2 = mold assembling; M3 = placement of reinforcement; M4 = casting; M5 = curing; M6 = mold stripping; M7 = finishing/repairing; M8 = storing; M9 = transportation.

to the construction sites by trucks or trailers. Delivery of PCs to the construction sites can be delayed due to truck failure. Eventually, PCs arrive at the construction sites; but before hoisting them to their final destination, the responsible site engineer scrutinizes the delivered PCs to ensure that they are matching with construction drawings. In case of finding defects that cannot be overlooked, the PCs are repaired and installed at their positions. However, if the repaired PC is still rejected by the site engineer, an alternative PC is ordered from the precast plant. Finally, the incurred penalty cost and production costs are recorded for the purpose of decision making. The processing times of the different operations of the PSC are taken from (Wang et al., 2018b) and summarised in Tables 2 and 3.

Table 3: Processing times of tasks at the echelons of material supplying and construction site.

Process	Duration (hour)
Receiving PC order	TRIA (0.05, 0.1, 0.15)
Ordering material	TRIA (0.05, 0.1, 0.15)
On-site inspection of PCs	TRIA (0.15, 0.35, 0.55)

5 THE SIMULATION-BASED OPTIMIZATION APPROACH

The developed simulation model is integrated with an optimization package in order to find the optimum PCs sequences. The inputs, decision variables and objective function are elucidated along the following subsections.

5.1 Objective Function

Commonly, pre-casters are contemplating minimization of production cost and penalty cost, as reducing the first one enables them to repay financing costs while minimizing the second one promotes their reputation. The two objective functions are adopted from (Wang and Hu, 2017) and (Wang et al., 2018b), respectively. The penalty cost, $f_{pn}(s)$ is represented by equation (1) while the production cost, $f_{pr}(s)$ is represented by equation (2).

$$f_{pn}(s) = Min \sum_{j=1}^{n} \left[\alpha_j Max\left(0, C_j - d_j\right) + \beta_j Max\left(0, d_j - C_j\right) \right] \tag{1}$$

Where s is the sequence of precast components; C_j is completion time of each job (PC) j at the last process; d_j is contracted due date for each job (PC) j; α_j and β_j are the tardiness and earliness penalties per unit j.

$$\begin{aligned} f_{pr}(s) &= LC(s) + IC(s) \\ &= \alpha_{\mathrm{l}} \times LT(s) \times N_l + \alpha_{\mathrm{i}} \times LT(s) \end{aligned} \tag{2}$$

Where $LC(s)$ is labor cost at sequence s; $IC(s)$ is inventory cost at sequence s; α_{l} and α_{i} are empirical cost coefficients equal 3$/(labor*hour) and 12.3$/day; N_l is number of labours; $LT(s)$ is time in hours spent by precast components, ordered in a sequence s, from receiving the order to be approved on site.

However, summing the two objectives into one objective function may be unsuitable as the production cost is often higher than the penalty cost, and therefore it is expected that the production cost will dominate the penalty cost. This situation might lead to solutions focus only on minimizing production costs at the expense of penalty cost. So, the two objectives are combined into one non-dimensional fitness function with equal weights by using a function transformation method, mentioned in

(Marler and Arora, 2005). The Fitness function, $f_t(s)$ is represented by equation (3).

$$f_t(s) = W_{pn} \times \left(\frac{f_{pn}(s) - f_{pn}^*}{f_{pn}^*}\right) + W_{pr} \times \left(\frac{f_{pr}(s) - f_{pr}^*}{f_{pr}^*}\right) \qquad (3)$$

Where f_{pn}^* and f_{pr}^* are minimum or approximate minimum values of penalty and production costs; W_{pn} and W_{pr} are relative weights of penalty and production costs.

5.2 Decision Variables

The solution of the optimization procedure is the sequence *(s)* of producing ten PCs. For example, 7-9-2-5-4-10-8-6-3-1 is a PC production sequence where the first PC to be processed is component 7; the second one is component 9; and so forth. Understandably, each PC may have a different processing time at each process in the PSC, and all jobs (PCs) have to be processed in the same operating sequence of all machines (processes). So, it is a typical flow shop sequencing problem.

5.3 Constraints

Any solution becomes feasible only if each PC has a unique ordering from 1 to 10. For example, 7-9-2-5-4-10-7-6-3-1 is an infeasible solution because component 7 is processed twice and component 8 is not scheduled at all. The following constraints ensure the feasibility of the generated solutions. For instance, if we have a number of PCs n and each PC j, where $j \epsilon \{1, \ldots, n\}$, must be processed with a sequence number i, where $i \epsilon \{1, \ldots, n\}$. A binary variable x_{ij} will equal one if the PC j is processed in i^{th} order and zero otherwise.

$$\sum_{j \in n} x_{ij} = 1 \quad \forall\, i \in n \qquad (4)$$

$$\sum_{i \in n} x_{ij} = 1 \quad \forall\, j \in n \qquad (5)$$

5.4 The Simulation Optimization Technique

OptQuest® for Arena® is used for simulation based optimization. OptQuest® is fully integrated with Arena®; it utilizes scatter search, tabu search and neural networks as search techniques. By using these techniques, OptQuest® establishes a new set of decision variables after evaluating the objective function generated by the simulation model in a cyclic manner until a predefined stopping criteria is achieved (Automation, 2013).

6 RESULTS AND DISCUSSION

In this section, the aforementioned simulation optimization approach is applied to find out whether considering or ignoring risks in the PSC changes the optimum PCs sequences generated from the optimization process. For more clarification, this approach is conducted twice, with and without considering risks. The obtained results are discussed and analyzed along the following sub-sections.

6.1 In Case of Considering Risks

To launch the optimization process, the number of replications and stopping criteria have to be specified. Regarding the number of replications, 800 replications are used to obtain solutions with avergae half width less than 5%. It is worth mentioning that (Wang et al., 2018b) used 1000 replications. Secondly, the stopping criteria is determined to terminate the optimization process when there is no improvement in the fitness value for a consecutive 200 simulation iterations. This number of iterations is determined after conducting some preliminary analysis.

Finally, the optimization process is accomplished in about 160 minutes with 250 simulation iterations by using a laptop with Intel(R) Core(TM) i7-6500U 2.50 GHz processor, 8.00 GB of RAM and running a Windows 10 Education 64-bit operating system. The top near optimum PCs sequences are listed in Table 4 with their values of penalty and production costs.

Table 4: Near Optimum sequences produced when considering risks with its penalty and production cost.

Sequence ID (s_{ri})	PCs sequence	Penalty cost	Production cost
s_{r1}	7-9-2-5-4-10-8-6-3-1	479.0	10594.0
s_{r2}	10-9-2-5-4-7-8-6-3-1	502.2	10636.8
s_{r3}	2-10-9-8-7-5-3-6-1-4	511.9	10622.2
s_{r4}	7-9-2-6-4-10-5-8-3-1	509.1	10730.3

6.2 In Case of Ignoring Risks

The same procedure is repeated again, but this time after discarding the risks. Eliminating the risks in the developed DES model is simply done by setting the probabilities of the five risks to zero. By trial and error, ten replications are used to ensure generating reliable solutions with about 5 percentage avergae half width. Eventually, the optimization process is completed after 500 generations and it took about 15 minutes by using the same hardware mentioned in section 6.1. The top near optimum sequences are listed in Table 5. To explore the penalty and production costs of these schedules, in case of applying them to a PSC suffered from the five identified risks. Table 6 presents the values of the penalty and production costs of these schedules if they are applied to the PSC without eliminating the original risks' probabilities mentioned in Table 1.

Table 5: Near optimum sequences resulted in case of ignoring risks with its penalty and production cost.

Sequence ID (s_i)	PCs sequence	Penalty cost	Production cost
s_1	1-2-9-7-8-5-10-6-3-4	200.4	9212.5
s_2	4-2-9-7-6-5-10-8-3-1	203.1	9212.5
s_3	3-2-9-7-8-5-10-4-6-1	203.3	9212.5
s_4	2-6-7-9-4-5-8-10-3-1	204.7	9212.5

Table 6: Values of penalty and production cost when applying near optimum schedules (s_1 *to* s_4) on PSC with the associated risks.

Sequence ID	With considering risks		Percentage increase	
	Penalty cost	Production cost	Penalty cost	Production cost
s_1	537.4	10904.7	168%	18.4%
s_2	564.9	11128.7	178%	20.8%
s_3	525.2	10847.9	158%	17.8%
s_4	598.9	11198.5	193%	21.6%

Making a comparison between Tables 4 and 5 reveals that the near optimum PCs sequences generated after risk consideration in PSC (schedules from s_{r1} to s_{r4}) are totally different from those obtained when neglecting the risks (schedules from s_1 to s_4). More importantly, applying the PCs sequences generated without considering risks (schedules from s_1 to s_4) to a PSC exposed to the predefined risks may lead to poor performance in terms of both high penalty and production costs, as shown from the second column of Table 6. The third column of the same table represents the percentage increase in penalty and production costs in comparison with their values in Table 5. These percentages illustrate how production and penalty costs are escalated when taking risks into consideration, and interestingly they show that the penalty cost is more sensitive to these risks than the production cost. This means that the reputation and credibility of pre-casters to deliver PCs on contracted due dates may be significantly harmed if they ignore risks of PSC. In addition to that, simulating PSC with risks requires a larger number of replications (800 replications) than the number used in case of ignoring risks (only 10 replications) and as a result the optimization process takes longer time when considering risks in the PSC. The long solution time may pose a problem to production managers who need faster ways to determine PCs sequences. So, this might call for using other simulation optimization methods to shorten the solution time such as the response surface methodology.

7 CONCLUSION

Risks are ubiquitous and inevitable in the different echelons of the PSC, and hence pre-casters need to consider them when making operational decisions such as sequencing of PCs. In spite of pernicious effect of these risks propagating throughout the PSC, as pointed in the previous studies, the effect of these risks on determination of the optimum PCs sequences has not yet been addressed. To bridge this gap, firstly, echelons of the PSC accompanied by their risks are simulated using a discrete event simulation model. After that, it is linked with an optimization solver to generate the optimum PCs sequences with and without considering risks in the PSC. Making a comparison between the optimum PCs sequences generated with and without considering risks reveals some remarkable points:

1- Near optimum PCs sequences obtained with considering risks are totally different from that produced in case of discarding risks.

2- Applying the generated near optimum PCs sequences without considering risks on a PSC plagued by risks causes high penalty and production costs.

3- The penalty cost is escalated more than the production cost in case of taking PSC risks into consideration.

4- Considering risks in PSC increases variability which in turn prolongs the computational time.

Having discussed all of this, this study provides pre-casters with quantitative evidence for the importance of integrating the risk management with the PSC. Since allocating resources to conduct the risk management procedures can help pre-casters not only in minimizing the probability and impact of the identified risks, but also in making better operational decisions such as determining the optimum PCs sequence to ensure higher service level with minimum production cost. Hence, investing in making a reliable risk management plan has dual benefits to precasters. This can be backed by the study findings that found that conducting simulation optimization without considering risks in the PSC, to find the optimum PCs sequence, may backfire and lead to PCs sequences which cause high production costs and vast deviations from the contracted due dates. Moreover, this study provides the practitioners with the way to link Arena® model with Optquest® to solve precast flow shop sequencing problem. However, using Optquest® for Arena® to solve this problem when considering risks in the PSC took long time due to high variability. This issue may be worsened in case of using larger number of decision variables and replications, which poses a problem for pre-casters who need quicker way to make such operational decisions. To remedy this, using another simulation optimization methods such as response surface methodology may be fruitful in order to shorten the optimization time.

In line with this study, other research questions need to be answered such as how considering the PSC risks can influence other operational decisions such as resource allocation and inventory management in the precast plants.

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