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Digital Twins Model for Cranes Operating in Container Terminal

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Abstract: The paper presents an Integrated Maintenance Decision Making Model (IDMM) concept for cranes under operation especially into the container type terminals. The target is to improve cranes operational efficiency through minimizing the risk of the Gantry Cranes Inefficiency (GCI) results based on implementation the Digital Twins concept. The proposed model makes a joint transportation process and crane maintenance scheduling, relevant to assure more robust performances in stochastic environments, as well as to assess and optimize performances at different levels, from components and transport device to production systems (container terminal). The crane operation risk is estimated with a sequential Monte Carlo Markov Chain (MCMC) simulation model and the optimization model behind of IDMM is supported through the Particle Swarm Optimization (PSO) algorithms. The developed model allows the terminal container operators to obtain a maintenance schedule that minimizes the GCI, as well as establishing the desired level of risk. The paper demonstrates the effectiveness of the proposed maintenance decision making concept model for cranes under operation with use the data coming from of a real container terminal (case study).

Keywords: Gantry cranes, Digital twins, Maintenance scheduling, Operation risk analysis, Monte Carlo simulation, Container terminal.

1. INTRODUCTION

In the last two decades, container transportation system has been faced under increasing development and it is predicted that this increase will have a rate of about 10% until 2020 (Widarto & Handani, 2015). This fact shows the importance of container transportation system as a key role of container terminals to link between sea and land. Although container terminals are growing their capacity to respond to these current demands, the rapid increase in the transportation of containerized goods has created a continuous need for the optimal use of equipment and the facilities in the port, so that the operational costs could be decreased, and the performance of the ports could be improved. In the container terminal operating system, gantry cranes are critical transport devices and major bottleneck restricting the working efficiency of the harbour. Container terminal managers pay more and more attentions to improve operational efficiency of gantry cranes (Haoyuan & Qi, 2017; Euchi et al., 2016; Dadashi et al., 2017; Abourraja et al., 2017)) and the Maintenance Process is one of fundamental aspects to ensure its proper functioning (Smoczek & Szpytko, 2012; Smoczek & Szpytko, 2017; Liu et al., 2018). The increasing of loading/ unloading activities requires the proper readiness of supported infrastructure, including gantry cranes, and the Digital Twins concepts (Qi and Tao (2018)) are the perfect tool to improve the design, production planning, manufacturing, and maintenance in this system.

Generator support systems, including power transformers and transmission lines, are examples of complex system which have a dynamic characteristic time by time (Szpytko, 2004). Stochastic type methods can simulate the dynamic behaviour of a system time by time and in some conditions and assumptions. The paper is focusing on developing a joint transportation process and crane maintenance scheduling relevant to assure more robust performances in stochastic environments, as well as to assess and optimize performances at different levels, from components and transport device to production systems (container terminal). The Integrated Maintenance Decision Making Model (IDMM) concept for cranes under operation especially into the container type terminals will be proposed. The digital twins type model target is to improve cranes operational efficiency through minimizing the risk of the Gantry Cranes Inefficiency (GCI) results implementation the maintenance scheduling process (see Appendix A).

2. MATERIALS AND METHODS

In this section, a vessels demand, gantry cranes, generator support system, power transformers and transmission lines stochastic mathematical model for a container terminal are defined. The Monte Carlo Markov Chain (MCMC) model used to estimate the GCI risk indicator in container terminal and the optimization model behind of IDMM used for gantry cranes/generator support system is formalized.

2.1 Vessels demand modelling

The period of time between the arrival of two consecutive vessels in this paper is considered that follows an exponential distribution with parameter λ_{VF}, which we will denote in this

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investigation as $VF_n \sim E(\lambda_{VF})$, where n = 1, 2, …, VN - number of vessels that arrive in one year at the container terminal. One of the vessel features is its length and capacity. Each vessel carries several containers to the port for unloading, and each vessel loads a specific number of containers and leaves the port. The containers number VC_n of the n-th vessel is chosen according to empirical distribution shown in Table 1, generating u uniformly distributed random numbers [0, 1].

Table 1. Empirical distribution

Length (meters)	Capacity (containers number)	Class (%)
100	50	$0 \le u \le 4.81$
120	100	$4.81 < u \le 7.80$
140	200	$7.8 < u \le 10.05$
150	250	$10.05 < u \le 22.67$
160	300	$22.67 < u \le 32.30$
170	400	$32.3 < u \le 41.60$
180	600	$41.6 < u \le 47.59$
190	800	$47.59 < u \le 52.94$
205	1000	$52.94 < u \le 56.36$
215	1100	$56.36 < u \le 66.09$
225	1200	$66.09 < u \le 76.68$
240	1300	$76.68 < u \le 82.03$
260	2000	$82.03 < u \le 91.66$
280	3000	$91.66 < u \le 96.79$
300	4000	$u > 96.79$

The function that models the containers number behavior $VC_n(t)$ in the n-th vessel that arrives at the port, at the time instant t is defined in equation below:

$$VC_n(t) = \{ VC_n \quad \text{if} \quad VF_{n-1} \le t < VF_n \qquad (1)$$

where: n = 1, 2, …, VN.

2.2 Gantry cranes modelling

The gantry cranes operation is continuous, eventually fails and is repairable. This random behavior can be described from Markov processes (Soszynska, 2012). Considering the operation effectiveness of the container gantry crane, in this paper, we fix that the system and its components have two states z = 0, 1. In the two-state model, the gantry cranes are considered fully available (z = 1) or totally unavailable (z = 0). According to the standard systems, each gantry cranes should carry out 25 moves per hour which is equal to 144 seconds for every movement (Azimi & Ghanbari, 2011). To simulate a real operation, the j-th number of movements $C_{GC_{i,j}} \sim N(\mu_{GC_i}, \sigma_{GC_i})$, where μ_{GC_i} is the average move/hour and σ_{GC_i} the standard deviation assumed. The stochastic capacity $U_{GC_{i,j}}(t)$ at the time instant t of a gantry cranes i is determined by the TTF_i (time to failure), TTR_i (time to repair) and $C_{GC_{i,j}}$. The parameters TTF_i, TTR_i and $C_{GC_{i,j}}$ allow to simulate with (2) the behavior of $U_{GC_{i,j}}(t)$ generating k-th independent random numbers, assuming $TTF_{i,k} \sim W(\alpha_i, \beta_i)$ and $TTR_{i,k} \sim N(\mu_i, \sigma_i)$, where α_i and β_i are the shape and scale parameters of the Weibull distribution function respectively, μ_i is the average time repair and σ_i the standard deviation assumed of the Normal distribution function respectively for each i-th gantry crane. The model proposed to simulate gantry cranes capacity is defined below:

$$U_{GC_{i,j}}(t) = \begin{cases} C_{GC_{i,j}} & \text{if} \quad t < S_{1_{i,m}} + S_{2_{i,m-1}} \\ 0 & \text{if} \quad S_{1_{i,m}} + S_{2_{i,m-1}} \le t < S_{1_{i,m}} + S_{2_{i,m}} \end{cases} \qquad (2)$$

where: i = 1, 2, …, N_{GC}; j = 1, 2, …, NH (8760 hours/ year); k = 1, 2, …, MN_i; $S_{1_{i,m}} = \sum_{k=1}^{m} TTF_{i,k}$ for m = 2, 3, …, MN_i and $S_{2_{i,m}} = \sum_{k=1}^{m} TTR_{i,k}$ for m = 2, 3, …, MN_i.

The container terminal capacity $TC_n(t)$ defined in equation (3) is determined by the j-th gantry cranes total capacity in the container terminal TC_{GCn} and the time of each vessel in the container terminal $VF_{n-1} \le t < VF_n$:

$$TC_n(t) = \left\{ TC_{GCn} = \sum_{j=VF_{n-1}}^{VF_n} \sum_{i=1}^{N_{GC}} U_{GC_{i,j}}(t) \quad \text{if} \quad VF_{n-1} \le t < VF_n \right. \qquad (3)$$

where n = 1, 2, …, VN.

On the other hand, one of the factors that affects the capacity of container terminals, is not stochastic and is not considered a random phenomenon, it is type maintenance strategy used into gantry cranes. The maintenance is contemplated within the strategies of a container terminal because it guarantees planned work time for the cranes. Maintenance is the activity designed to prevent failures in the production process and in this way reduce the risks of unexpected stops due to system failures (see Appendix A). In the case of preventive maintenance strategy, it is the planned activity in the vulnerable points at the most opportune moment, destined to avoid failures in the system. It is carried out under normal conditions, that is, when the productive process works correctly. In a container terminal, to perform some preventive maintenance tasks it is necessary that the gantry crane does not work, and this causes loss of capacity in the terminal. Due to this reason, it is advisable that this preventive maintenance be carried out at the time of the year where the least frequency of vessels exists, so that equilibrium and adequate flow are guaranteed in the container terminal. To consider this effect, in this work the parameters $TTM_{i,k}$ (start time to maintenance) and $TDM_{i,k}$ (time duration maintenance) are introduced and the equation (2) is redefined by equation (4), as shown below:

$$U_{GC_{i,j}}(t) = \begin{cases} C_{GC_{i,j}} & \text{if} \quad t < S_{1_{i,m}} + S_{2_{i,m-1}} \\ 0 & \text{if} \quad S_{1_{i,m}} + S_{2_{i,m-1}} \le t < S_{1_{i,m}} + S_{2_{i,m}} \\ 0 & \text{if} \quad A_{1_{i,n}} + A_{2_{i,n-1}} \le t < A_{1_{i,n}} + A_{2_{i,n}} \end{cases} \qquad (4)$$

where: i = 1, 2, …, N_{GC}; j = 1, 2, …, NH (8760 hours/ year); $S_{1_{i,m}} = \sum_{k=1}^{m} TTF_{i,k}$ for m = 2, 3, …, MN_i; $S_{2_{i,m}} = \sum_{k=1}^{m} TTR_{i,k}$ for m = 2, 3, …, MN_i; $A_{1_{i,n}} = \sum_{k=1}^{n} TTM_{i,k}$ for n = 2, 3, …, NK_i; $A_{2_{i,n}} = \sum_{k=1}^{n} TDM_{i,k}$ for n = 2, 3, …, NK_i.

2.3 Generator modelling

The generating unit operation is continuous, eventually fails and is repairable. This stochastic behavior can be described with Markov processes (Yan et al., 2016). The two - state model is used to represent the generators that operate as base