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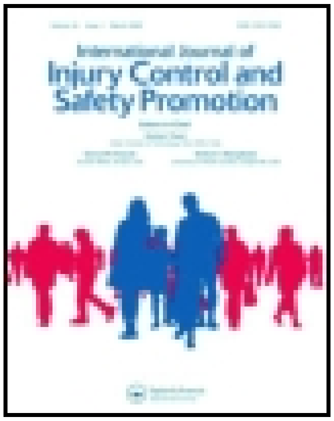

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Being a powerful tool in modelling industrial and service operations, Petri net (PN) has been extremely used in different domains, but its application in safety study is limited. In this study, we model the gantry crane operations used for industrial activities using generalized stochastic PNs. The complete cycle of operations of the gantry crane is split into three parts namely inspection and loading, movement of load, and unloading of load. PN models are developed for all three parts and the whole system as well. The developed PN models have captured the safety issues through reachability tree. The hazardous states are identified and how they ultimately lead to some unwanted accidents is demonstrated. The possibility of falling of load and failure of hook, sling, attachment and hoist rope are identified. Possible suggestions based on the study are presented for redesign of the system. For example, mechanical stoppage of operations in case of loosely connected load, and warning system for use of wrong buttons is tested using modified models.

Keywords: gantry crane operations; petri nets; reachability tree; hazardous states; safety actions

1. Introduction

Gantry cranes are mostly used for transfer of materials on ports and other industrial places. It eases the movement of heavy materials, with the cost of safety during its use. Occupational fatalities and injuries caused by the operation of cranes pose a serious problem. Crane activities are responsible for 4% of the reported accidents. Several studies have been conducted examining the causes of injuries and deaths from cranes (Aneziris et al., 2008; Häkkinen, 1978; Neitzel, Seixas, & Ren, 2001; Suruda, Egger, Liu, & Stat, 1997; Yow, Rooth, and Fry, 2000)**.** According to these studies and the crane accidents reported by the National Institute of Occupational Safety and Health (NIOSH) and the US Navy, accidents may be grouped into the following categories: falling loads, swinging loads, collapsing or overturning of cranes, crushing between moving parts of cranes, falls of people from cranes and electrocution.

There are several reasons attributed to crane accidents. The hazard theory states that hazard and accident are the two sides of a coin (Nicholson & Ridd, 2014). A *hazard* is a set of conditions representing a state from which there is a path to an accident. A state σ is hazardous if and only if there exists an accident state σ_m and a sequence of transitions $s \in T$ such that of $f(\sigma, s) = \sigma_m$, when f represents 'function of'. Hazards can be categorized by the aggregate probability of the occurrence of the individual conditions making up the hazard and by the seriousness of the resulting accident (Arunraj, Mandal, & Maiti, 2013). An accident is an unplanned event or series of events that results in death, injury, illness, or damage or loss of property or equipment (Leveson & Stolzy, 1987). Accidents can have severity varying from catastrophic to negligible (Arunraj & Maiti, 2009; Maiti, Khanzode, & Ray, 2009).

Traditional approaches used in accidents studies are based on techniques like preliminary hazard analysis, failure mode and effect analysis (FMEA) and fault tree analysis (FTA) (see Kumamoto & Henley, 2000 for details). The steps involve hazard identification, risk assessment, risk prioritization and risk control (Aneziris et al., 2008; Khanzode, Maiti, & Ray, 2012). Fault tree and event tree are the commonly used techniques in assessing the safety issues for systems as demonstrated by Doytchev and Szwillus (2009), Vestrucci (2013) and Wang, Jiang, Xia, and Cao (2010). But fault tree technique suffers from number of limitations like it is static in nature and fails to show the flow of the process. Petri net (PN) is an excellent tool to analyse the discrete systems and used by many researchers in the field of safety (Hura & Atwood, 1988; Leveson & Stolzy, 1987; Liu & Chiou 1997; Peterson, 1981; Yang & Liu, 1997). Some other applications include the PN modelling of the information flow (Song & Wu, 2012) and the dynamic event-driven modelling (Essink, 1991; Pérez & Gutiérrez, 2015; Wang, 2007). The motivation for this work is to see safety from the system behaviour point of view and extract the requirements for ensuring safety.

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In this study, we show how PN can be used to model gantry crane operations of loading and unloading of hardware as it can provide a better way to analyse the system safety in comparison with the FTA (Abecassis et al., 2015; Akgün, Gümüşbuğa, & Tansel, 2015; Liu & Chiou, 1997; Liu & Yokoyama, 2015; Sarkar, Panja, & Das, 2015; Yang & Liu, 1997). Many hazardous events crop up during gantry crane operations. The hazardous events that might occur include not only the mechanical failure of components or sub-systems, but also the errors committed by the operators. By doing so, we can focus on the conditions which might lead to dangerous consequences or failures. It is also possible to use such a model to analyse safety during operations and fault tolerance requirements. We are considering the use of stochastic PNs (Murata, 1989), with timed as well as untimed transitions (see Section 2 for theory). There are certain events which occur immediately during the operation and are incorporated using immediate transitions. Certain processes are also present which take some time and timed transitions are used for them.

2. Petri net modelling for existing gantry crane operations

A PN is a particular kind of bipartite directed graphs populated by three types of objects: 'Places', 'Transitions', and 'Directed arcs' (Peterson, 1981). Directed arcs connect places to transitions and transitions to places. In its simplest form, a PN can be represented by a transition together with an input place and an output place. This elementary net may be used to represent various aspects of the modelled systems.

A PN is formally defined as a five-tuple $N = (P, T, I, O, M_0)$ (Murata, 1989), where

- $P = \{P1, P2, \ldots, Pm\}$ is a finite set of places;
- $T = \{t1, t2, \ldots, tn\}$ is a finite set of transitions;
- I: $P \times T \rightarrow N$ is an input function that defines directed arcs from places to transitions, where N is a set of non-negative integers;
- $O : T \times P \rightarrow N$ is an output function that defines directed arcs from transitions to places;
- M_0: $P \rightarrow N$ is the initial marking.

In PN a circle, O , represents a place and a bar, ▮, represents a transition. Here, we have used the generalized stochastic PN (GSPN). In GSPN, all the transitions are classified into two groups: immediate and exponential transitions. Immediate transitions fire as soon as they are enabled whereas exponential transitions take some time.

A GSPN is an eight tuple (P, T, I, O, INH, M_0, F, S), where

- (P, T, I, O, INH, M_0) is an inhibitor marked PN.
- T is partitioned into two sets: T_I of immediate transitions and T_E of exponential transitions.
- F: (R [M_0 X T_E]) $\rightarrow R$ is a firing function that associates to each $t \in T_E$ in each $M \in R$ [M_0], an exponential random variable with rate F (M, t).
- Each $t \in T_I$ has zero firing time in all reachable markings.
- S is a set of elements called random switches, which associates probability distribution to subsets of conflicting immediate transitions.

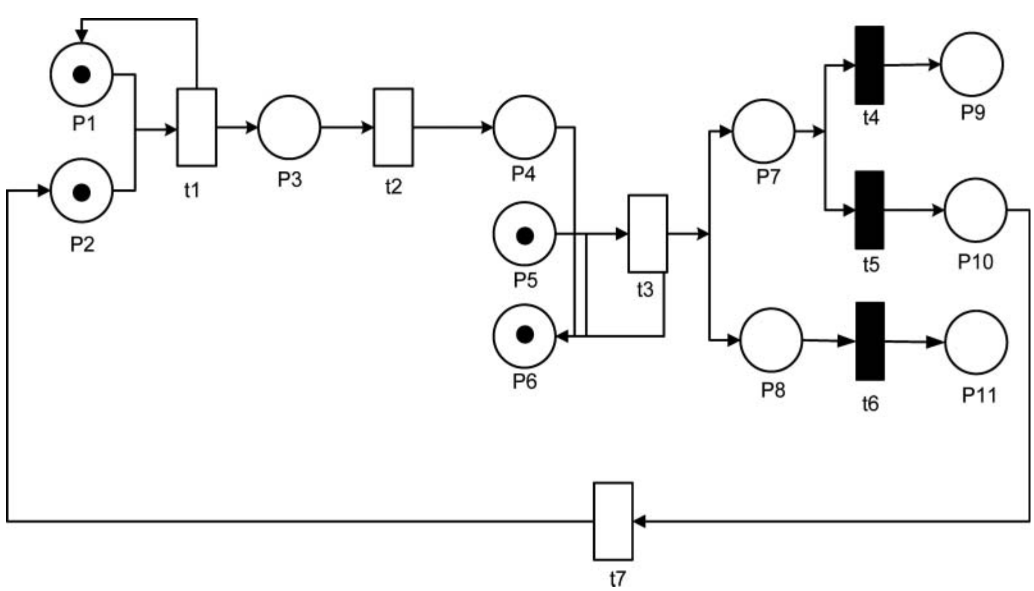

Figure 1. Petri net for inspection and loading of gantry crane.

Markings in which only exponential transitions are enabled are called tangible markings, while vanishing markings are those in which both immediate and exponential transitions are enabled. A white bar symbolizes a *timed transition* while a black bar stands for an *immediate transition* or *immediate transition*. Arrows or directed arcs join transitions to places and places to transitions. As an example the 'inspection and loading' of the gantry crane operation is shown in Figure 1. If the delay associated with transitions is fixed and known then these are called deterministic timed PNs and when delay is probabilistic, probabilistic nets are used. In probabilistic nets when delays are exponentially distributed, nets are known as stochastic nets as in Ramchandani (1974). In most of the cases, practical systems include both kind of the activities (i.e., timed and immediate) and hence, GSPN is a preferable model.

2.1. System description

The study was conducted in a government organization of India. Gantry crane used by the organization is of 25 tons capacity. There are two gantry cranes working in tandem at the port maintained by the organization. These cranes are used for loading and unloading heavy hardware on/from barge (motorized ship) for transportation. In a questionnaire survey administered to the experienced experts of the organization, it was found that catapulted and falling objects together cause around 21.3% of all possible hazardous events. In another in-house study of FMEA, it was found that hoist, hoist rope and hook assembly constitute around 30% of all failure modes that may result into falling of load. Till the time of the conductance of study, no major accident had taken place in the organization but attention is still required to ensure safety of personnel and material. In order to model the gantry system using PN, the operations are modelled in three parts: '*inspection and loading*', '*movement*' and '*unloading'*. The following sections illustrate them clearly.

2.2. Modelling for inspection and loading

2.2.1. Development of Petri nets

The PNs 'inspection and loading' part are shown in Figures 1 and 2. This part conveys that when both inspector ($P1$) and the crane ($P2$) are free, the crane is inspected ($t1$). The crane after inspection ($P3$) is positioned over load ($t2$) and then the hardware is attached to the crane ($t3$), provided the crane is ready ($P4$), load is available for attachment ($P5$), and workers are also ready ($P6$). From safety point of view, two situations may arise: load is attached safely to the crane ($P7$) or load is unsafely attached ($P8$). $P7$ may lead to safe lifting of the load to the desired height ($t4$) or mechanical or other failure (e.g. hook failure) occurs during the lift ($t5$). On the other hand, $P8$ may lead to falling of load during movement ($t6$) while $t4$ results into successful lifting of the load to the desired height ($P4$). $t5$ and $t6$ create unsafe situations, namely system in a damaged state ($P10$) and damaged load lying on the ground ($P11$), respectively. Finally, the system is recovered ($t7$) and made ready for inspection ($P2$). The places (P) and transitions (T) are shown in Table 1 and in terms of PN notations are shown below. In a PN model, places represent conditions and transitions represent events or processes. It is to be noted here that $I(t)$ and $O(t)$ define the inputs to transition t and outputs from transition t, respectively.

Table 1. Description of places and transitions for inspection and loading used in Petri net (Figure 1).

Places	Transitions
$P1$: Worker is free to inspect the crane	t_1 = Inspection of crane
$P2$: Crane is free for inspection	t_2 = Positioning of crane over load
$P3$: Crane after inspection	t_3 = Attachment of load
$P4$: Crane is ready to attach the load to be moved	t_4 = Safe lifting of the load to the desired Height
$P5$: Load to be moved is ready for attachment	t_5 = Mechanical or other failure (e.g. hook failure) during lifting of load
$P6$: Workers are ready to attach hardware to the crane	t_6 = Falling of load due to loose attachment/joint failure/ damaged hook/ damaged lifting rope/ damaged sling
$P7$: Load is safely attached to the crane	t_7 = System recovery after damage
$P8$: Load is unsafely attached to the crane	
$P9$: Load raised at a certain height	
$P10$: System in a damaged state after a mechanical or other failure (e.g. hook failure) during lifting the load	
$P11$: Damaged load lying on the ground	

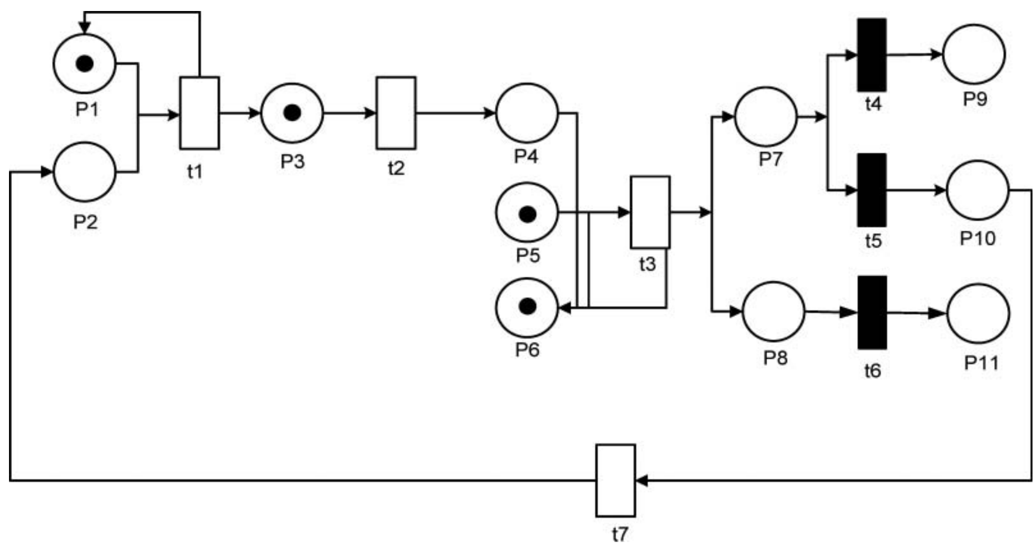

Figure 2. Petri net for inspection and loading after T1 fires.

$P = \{P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11\}$
$T = \{t1, t2, t3, t4, t5, t6, t7\}$
$M_0 = \{1, 1, 0, 0, 1, 1, 0, 0, 0, 0\}$

$I\{t1\} = \{P1, P2\}$	$O\{t1\} = \{P3\}$
$I\{t2\} = \{P3\}$	$O\{t2\} = \{P4\}$
$I\{t3\} = \{P4, P5, P6\}$	$O\{t3\} = \{P6, P7, P8\}$
$I\{t4\} = \{P7\}$	$O\{t4\} = \{P9\}$
$I\{t5\} = \{P7\}$	$O\{t5\} = \{P10\}$
$I\{t6\} = \{P8\}$	$O\{t6\} = \{P11\}$
$I\{t7\} = \{P10\}$	$O\{t7\} = \{P2\}$

Figure 1 also includes black dots in the circles, called *tokens*. A transition (t) is said to be *enabled* if all of its input places (P) have the required least number of tokens. Once a transition is enabled it becomes eligible to *fire*. Firing of a transition shows that the particular process has occurred. The firing might take place instantaneously, *immediate transition firing*, or the transition might fire after a delay of some time, *timed transition firing*. The presence or absence of a token in a place can indicate whether a condition associated with this place is true or false. With respect to Figure 1, the transition t_1 can be fired as its input places $P1$ and $P2$ have required number of tokens. Once $t1$ fires, the tokens from $P1$ and $P2$ are absorbed by $t1$ and passed on to the output place of $t1$ (i.e., $P2$). The next state of the PN is shown in Figure 2. The process of firing continues as long as any enabled transition remains in the PN. The places and transitions of the given PN in Figure 1 are tabulated in Table 1.

2.2.2. *Reachability tree and hazardous states*

In order to find out whether the modelled system can reach a specific state as a result of a required functional behaviour, it is necessary to find such a transition firing sequence which would transform a marking M_0 to M_i, where M_0 represents the initial marking as shown in Figure 1 and M_i is the specific state that can be achieved. The firing sequence from M_0 to M_i represents the required functional behaviour.

A marking M_i is said to be reachable from a marking M_0, if there exists a sequence of transitions firings which transforms a marking M_0 to M_i. The resultant sequence gives a tree-like structure called a reachability tree. Reachability analysis is conducted through the construction of the reachability tree (also called cover-ability tree). Given a PN N, from its initial marking M_0, we can obtain as many 'new' markings as the number of the enabled transitions. From each new marking, we can again reach more markings. Repeating the procedure over and over again results in a tree representation of the markings. Nodes represent markings generated from M_0 and its successors, and each arc represents a transition firing, which transforms one marking to another. Murata (1989) and Wang (2007) explained the concept of creating the reachability graph.

Figure 3 shows the reachability tree for loading and inspection, in which the nodes are labelled with the present marking, M (i.e., number of tokens present at different places) and transitions are shown along the arcs. Figure 3 shows some hazardous states which are circled out.

There are basically two hazardous events which might occur during loading and inspection. They are

- hook failure (or other mechanical failure) and
- falling of load due to loose attachment of load with the crane.

From Figure 1, it is seen that transition t_5 represents the hook failure (or other mechanical failure). If t_5 fires, it

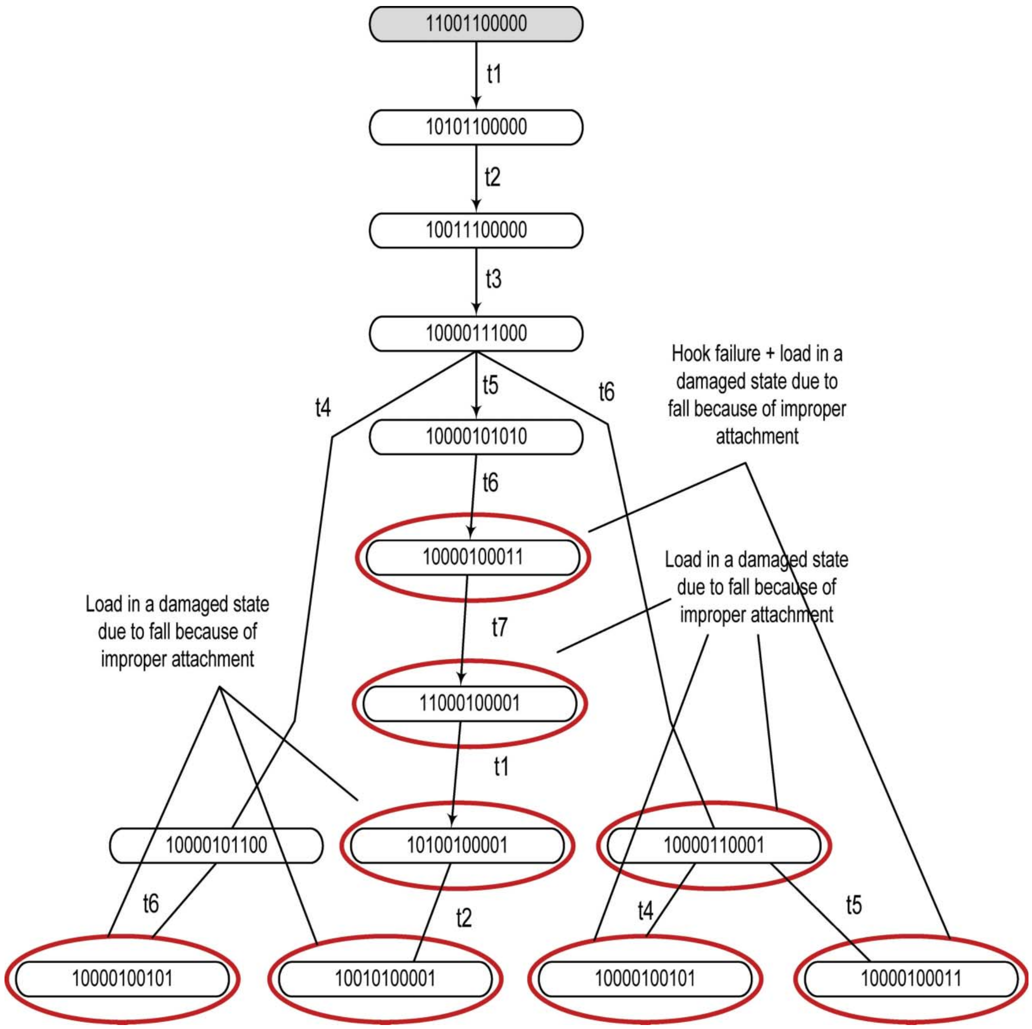

Figure 3. Reachability tree for inspection and loading.

sends a token in $P10$. The marking thus obtained denotes a hazardous state. Assuming that the crane was properly inspected before operation, the only reason for the transition t_5 to occur would be the overload condition of the crane. It might happen that the load to be lifted is above the capacity of the crane. This might add to excessive strain on the hook and other parts of the hoisting mechanism than it could hold otherwise. As a result, the failure occurs. The other hazardous event that could occur if the load is not properly attached to the crane is shown by the presence of a token in $P8$. Once a token comes in $P8$, $t6$ fires (load falls) and $P11$ gets a token (damaged load on the ground). It can be seen from the reachability tree that the marking with token in places $P10$ and $P11$ have been circled. These circled markings denote hazardous events. Therefore, measures must be taken to prevent the occurrence of such markings at all cost.

2.2.3. *Modified Petri net for safety improvement*

The reachability tree for inspection and loading delineates the situations for hazardous states to occur. Our objective here is to prevent the occurrence of such hazardous states (‘circled’ markings). For that, some modification needs to be done in the original PN. This could be done if we provide a mechanism, such that if the load is not properly attached, the system will not move and the load should then be reattached to the crane safely ($t8$). If this is done, $t6$ gets eliminated and eventually $P11$ as well will not occur. The modified PN for inspection and loading is shown in Figure 4.

The effect of changing the PN is visible in the new reachability tree (refer to Figure 5). It can be seen that now the number of places has reduced by one ($P11$ goes out). There are 10 places in total. Even though the place $P10$ gets a token in some markings, it might not lead to

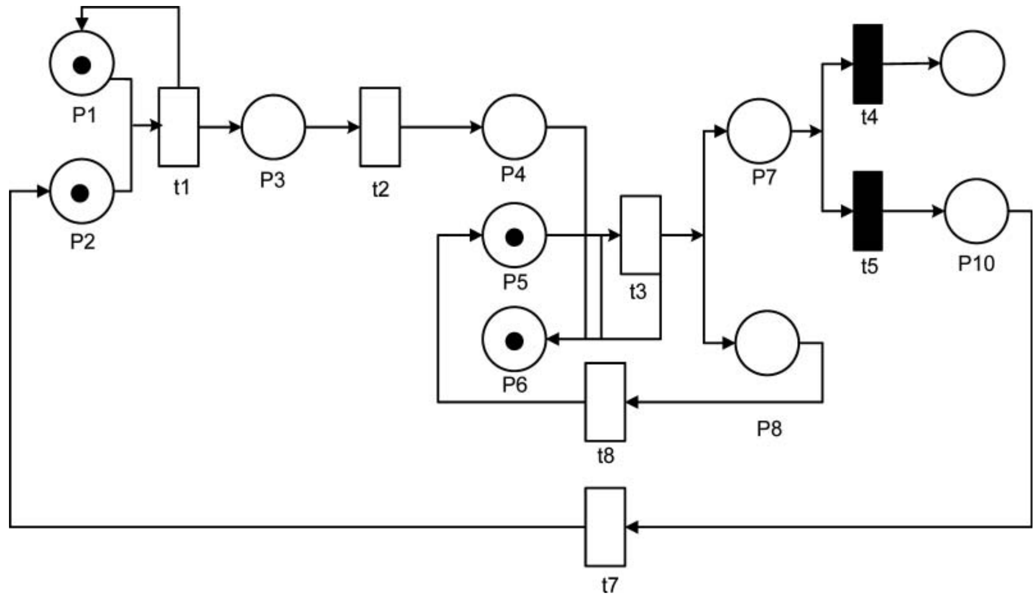

Figure 4. Modified Petri net for inspection and loading.

any hazardous event as system recovery is immediately done (transition $t7$ fires). Thus, the modified PN for inspection and loading shows a safe state of the system.

2.3. *Modelling for crane movement*

This PN model is depicted in Figure 6. The places and transitions are shown in Table 2. As crane movement takes place after loading, we continue denoting places (P) and transitions (t) as a continuation of Figure 1. Here, the crane is loaded and is ready to move with it. Two situations might arise. First, the crane is ready to move the hardware ($P11$). It needs the pathway to be free ($P14$). The pathway may or may not be free ($P15$) depending on various factors, such as some activity going on at place A ($P16$), some items occupying space A ($P17$) due to

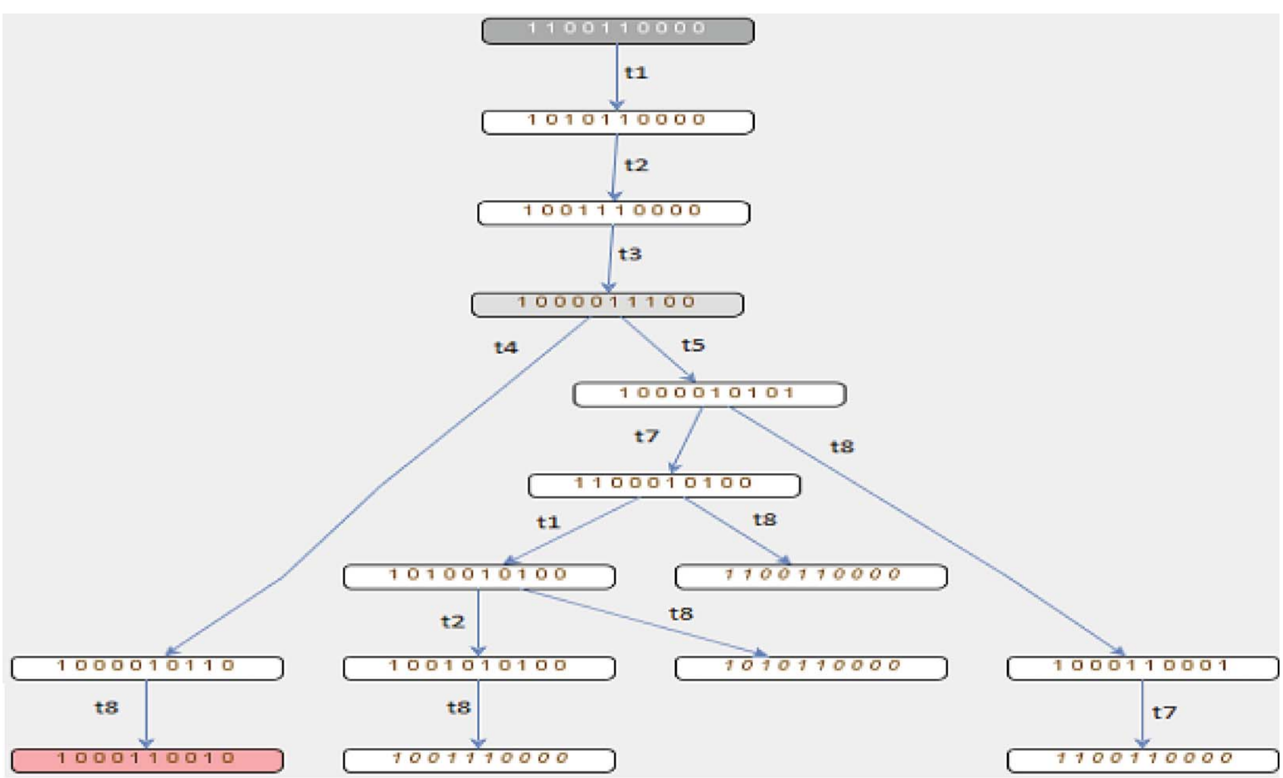

Figure 5. Reachability tree of modified Petri net for inspection and loading.

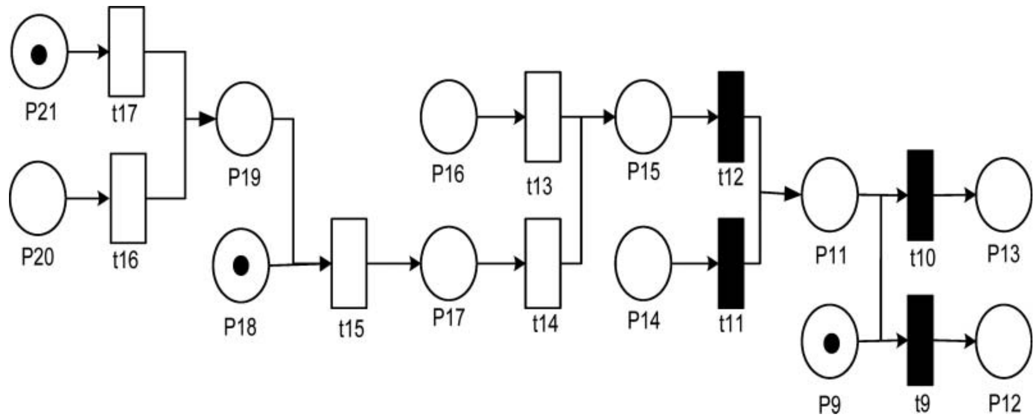

Figure 6. Petri net of movement of gantry crane.

absence or inadequate number of workers ($P18$) to clear space A. If the pathway is said to be free ($t11$) and the correct push button is pressed, the crane moves in the right direction ($t10$) and reaches the desired location B. Second, it might happen that a wrong push button is pressed ($t9$) and the crane starts moving in a wrong direction. The load might thus hit something if the pathway is not free. This needs to be taken care of immediately. The crane is needed to be stopped immediately and the load should be returned back to its initial position. The discrepancies are removed and the gantry crane is again inspected.

Here we have assumed that $P9$, $P18$ and $P21$ have got tokens initially. This signifies that load is raised at a certain height ($P9$), number of workers is less ($P18$) and some workers are absent ($P21$). $P12$ denotes that the system is in a damaged state as the crane hit something on its way. This is an undesirable event. It can be averted if transition $t9$ does not fire. If $t12$ does not fire, it means that the pathway was actually free and thus the probability of the load hitting any object or human on the pathway is negligible. In that case, $t9$ will not fire. If by chance $P11$ gets a token due to the firing of $t12$, there might be a possibility of occurrence of some danger. The corresponding reachability tree of the PN of movement is shown in Figure 7.

One way to prevent the dangerous situation to occur is to make use of the emergency stop. The emergency stop is to be used (by firing $t18$) as soon as the crane starts moving in any undesired direction (refer to Table 3). Then it needs to be returned back to its initial position ($t19$ fires). Thus, we get a modified PN (refer to Figure 8) wherein the hazardous place $P12$ has been eliminated. The reachability tree of the modified PN for crane movement is shown in Figure 9. The next section deals with the 'unloading' of hardware at the desired place.

2.4. *Modelling for unloading*

Herein the hardware has been positioned over the desired location B for unloading. Unloading could be done only

Table 2. Places and transitions for petri net for crane movement.

Places	Transitions
$P9$: Load raised at a certain height	$t_9 =$ Wrong push button is pressed and the load hits something (or is about to hit something)
$P11$: Crane is ready to move after pathway is said to be free	$t_{10} =$ Correct push button is pressed and the load moves in the right direction
$P12$: System in damaged state	$t_{11} =$ Result is communicated that the pathway is free
$P13$: Load at desired place at certain	$t_{12} =$ Movement is allowed even when the pathway is not free
$P14$: Pathway is free	$t_{13} =$ Result is communicated that the pathway is not free
$P15$: Pathway is not free	$t_{14} =$ Result is communicated that the pathway is occupied by some items
$P16$: Space occupied due to some activity at place A	$t_{15} =$ Items continue to occupy space at location A
$P17$: Space occupied by some items at A	$t_{16} =$ Result is communicated that the workers busy in other activities
$P18$: Number of workers is less	$t_{17} =$ Result is communicated that the workers are not present
$P19$: Workers are not present to remove the item(s)	
$P20$: Workers are busy in other activity	
$P21$: Workers are absent	

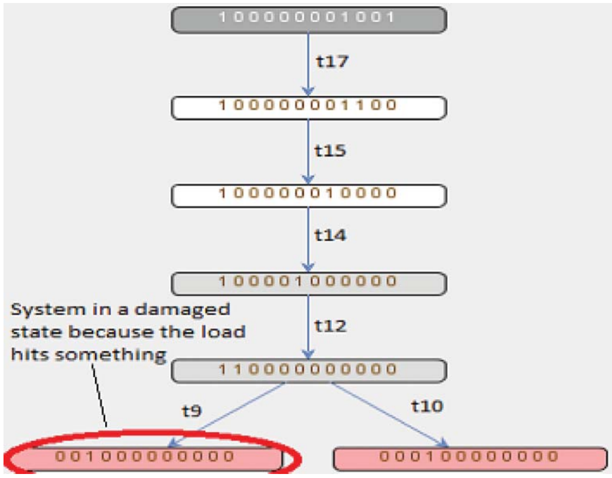

Figure 7. Reachability tree of crane movement.

Table 3. Additional places and transitions in the modified petri net for crane movement.

Places	Transitions
*P*22: Crane moving in undesired direction	t_{18}: Emergency stop applied
*P*23: Crane after being stopped urgently by using emergency stop	t_{19}: Crane returned back to its initial position
*P*24: Crane back in its initial position	

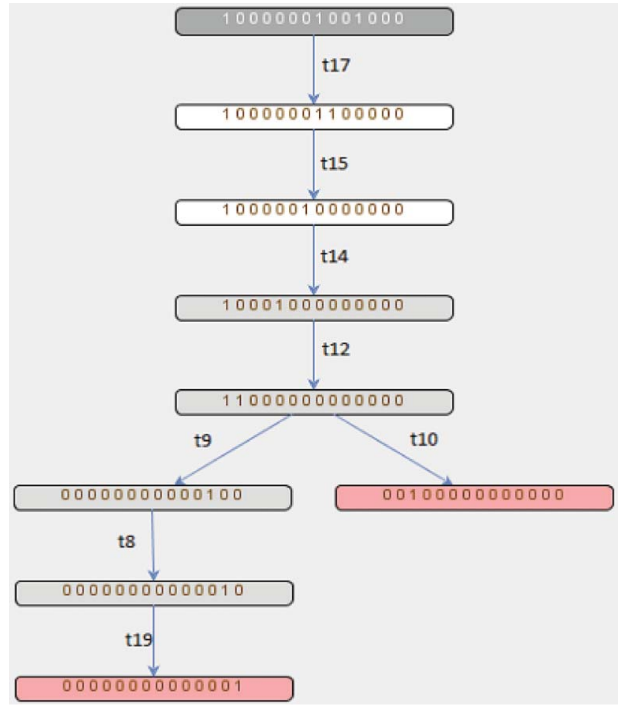

Figure 9. Reachability tree of modified petri net for crane movement.

when the space is free. The space for unloading may or may not be free depending on the cases whether any activity is going on there or some items are kept there. The PN is shown in Figure 10 and Table 4 describes the places and transitions used.

The corresponding reachability tree for unloading is shown in Figure 11. Here also we have a situation similar

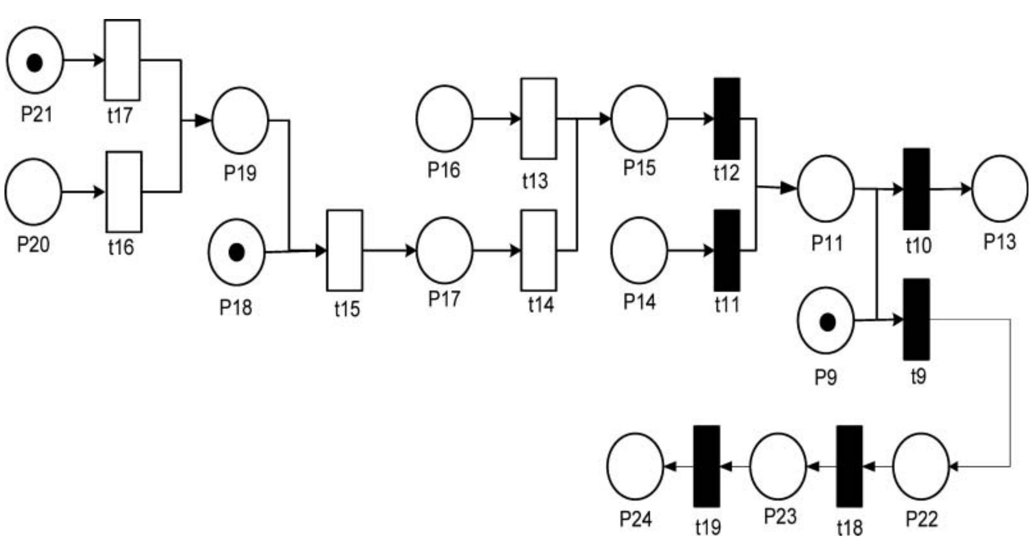

Figure 8. Modified form of Petri net movement.

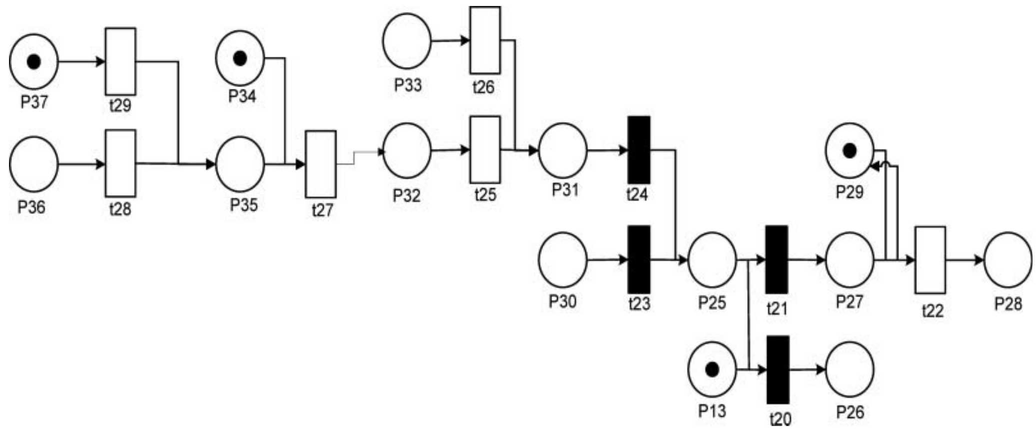

Figure 10. Petri net for crane unloading.

to that shown in case of movement. The load may not be unloaded smoothly or it may not be detached properly (*t*20). *P*26 should not have a token for the system to be safe. In other words, transition *t*20 should not be fired at all. This is possible if we apply the same measures which we have applied in case of movement and this will cause an additional condition to be satisfied so that the system becomes unstable.

2.5. *Modified Petri net model for the entire system*

Till now we have considered all the three sub-operations; first in the existing phase and then in the proposed modified phase, separately. If all the proposed modifications (in procedures to be followed or addition of physical components) are incorporated, we get a new PN model for the entire process as shown in Figure 12. We have shown the discrepancies in the existing operations and proposed the modified measures to be adopted. They are given in Table 5.

After making the desired modifications in the PN of the three sub-sections, they were combined together to get PN model for the entire operation. On combining the sub-sections, a new transition, *t*30, was introduced which denotes the gantry crane getting free and returning back to its initial position. Also transition *t*22 has a one more output place (*P*4) in the combined PN.

3. Conclusions

We have presented a case study of modelling of gantry crane operations using timed PN and an attempt was made to model safety aspects but we have not considered the varying probability of occurrence of different transitions. The potential hazardous events which are the most

Table 4. Places and transitions of petri net for crane unloading.

Places	Transitions
*P*13: Load at desired place at certain height	t_{20}: Load is not unloaded smoothly
*P*25: Place where load is to be kept is said to be free	t_{21}: Load is unloaded smoothly
*P*26: System in damage state during lowering	t_{22}: Load is unloaded at the desired position B
*P*27: Load is at desired place after lowering	t_{23}: Other activities continue at place A
*P*28: Crane is free	t_{24}: Space continues to be occupied due to less/ no workers
*P*29: Workers are free for unloading	t_{25}: Space continues to be occupied due to less/ no workers
*P*30: Place where load is to be kept is free	t_{26}: Other activities continue at place *A*
*P*31: Place where load is to be kept is not free	t_{27}: Absence of workers continues
*P*32: Space occupied by some items at place A	t_{28}: Activities being carried out at place *B*
*P*33: Workers are not present to remove the items	t_{29}: Items continue to occupy space at place *B*
*P*34: Number of workers is less	
*P*35: Workers are not present to remove the items	
*P*36: Workers are busy in some other activities	
*P*37: Workers are absent	

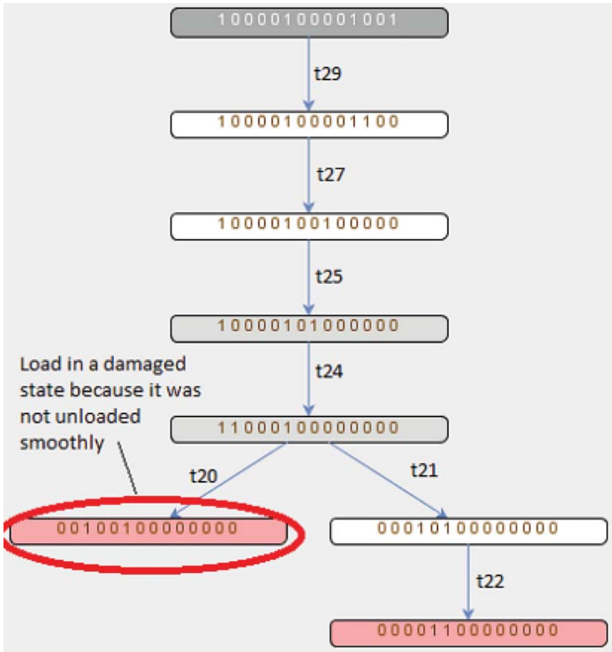

Figure 11. Reachability tree of Petri net for crane unloading.

probable causes of gantry crane accidents were considered, modelled through PN and shown through markings in the reachability tree. The corresponding PN was modified so that the hazardous situations could be eliminated.

Two major causes of mishap were identified: (1) falling of load due to loose attachment/damaged hook/joint failure/damaged sling/damaged lifting rope and (2) use of wrong push (control) button. The first cause is attributed to mechanical failure and second one arises because of negative human machine interactions.

Furthermore, the outcomes of the study can be summarized in following points.

- Regular maintenance and pre inspection of gantry crane.
- Installation of warning system and emergency stop (if missing) for gantry crane operations.
- Checking of sling, hook, hoisting rope, brakes, operating switches, and wirings before loading.
- Follow up of proper instructions among workers and operators during operation.
- The crane operator, inspector and the person giving signals for movement of crane should be properly trained and healthy.

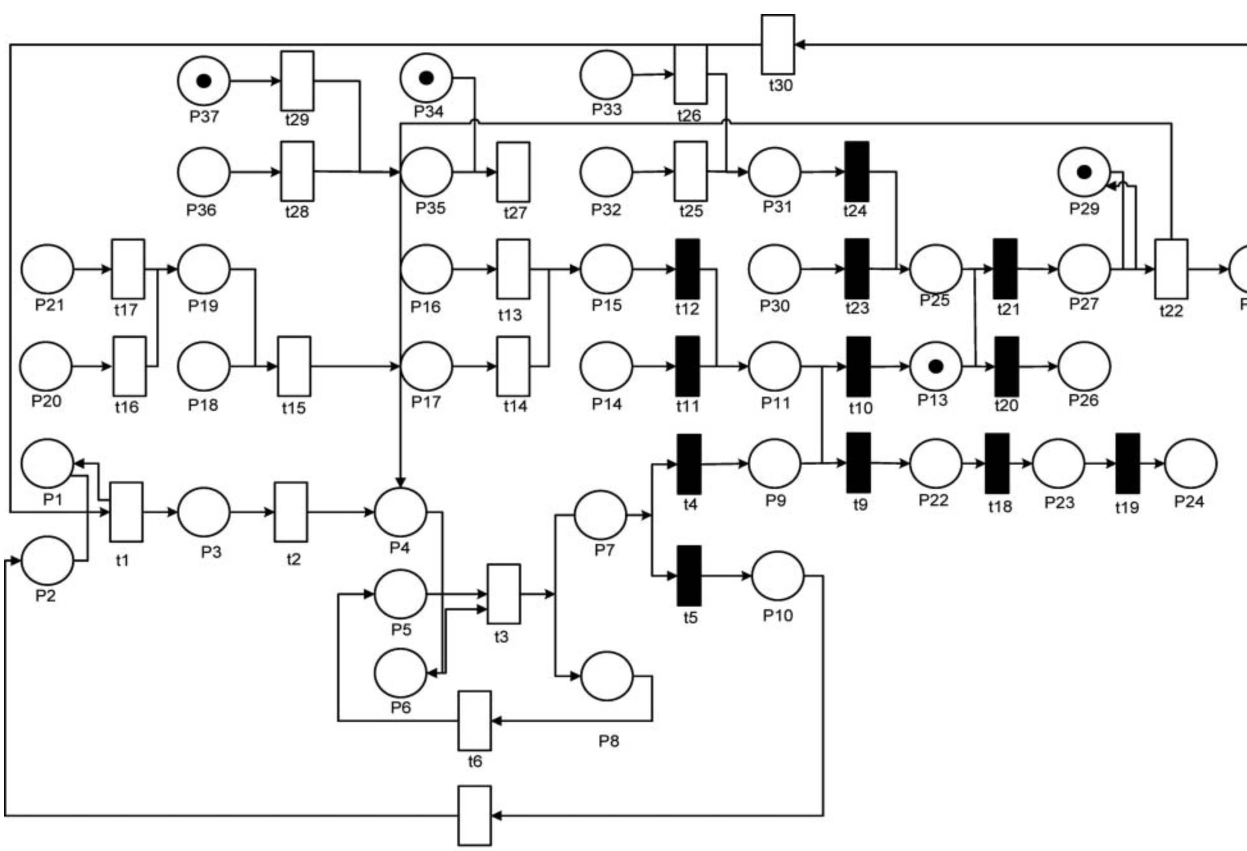

Figure 12. Petri net of the full gantry crane movement.

Table 5. Modification made with the existing system.

Sl. no.	Existing system	Effects	Modified system
1.	The required pre- inspection of joints, hook, lifting rope or sling might not be done properly. Besides, the load might not be attached securely to the hook.	Transition t_6 fires due to which the load falls and the system (load + crane) remains in a damaged state (i.e., P11, gets a token).	The inspection of hook, sling, joints and lifting rope must be done once again for any damage. The lifting capacity of the crane must be checked by a trained inspector before movement. Also if the load is found to be not properly secured, it should be reattached.
2.	A wrong push (control) button might be pressed during movement operation (i.e., transition t_9 fires)	This might lead to the movement of the load in undesired directions and the load might also hit any object. As a result the system (crane + load) might remain in a damaged state (i.e., P12 gets a token).	As soon as a wrong push (control) button is pressed, the emergency stop button (if present) must be applied (transition t_{18} fires and P23 gets a token).

- The area around the crane should be free of any obstacles for free movement of load and to prevent any undesired hitting of load.

The recommendations given above can be linked with Table 5 where system modifications are suggested. It is to be noted that the study modelled the crane operations to identify the hazardous situations and their preventive actions. Such models not only help in improving existing system from safety point of view but also help in designing new system with appropriate safety features. More studies in this line are therefore needed to be conducted under varied operational conditions in diversified facilities. Though the study is able to model inspection and loading, load movement and unloading of gantry crane operations, future studies should examine energy transfer events (either controlled/uncontrolled) as initiators of injury incidents and capture their effect through PNs models. Furthermore, the study considers timed PN to model operations of crane; a time-variant transition study can be explored in future.

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