COLLISION PREVENTION IN SINGAPORE STRAIT BY USING TIMED PETRI NET

Rino BOŠNJAK[1*], Danko KEZIĆ[2], Pero VIDAN[3], Zvonko KAVRAN[4]

[1, 2, 3]*Faculty of Maritime Studies, University in Split, Croatia*
[4]*Faculty of Transport and Traffic Sciences, University in Zagreb, Croatia*

Abstract. The problem of maritime traffic in Singapore Strait is traffic density, also the probability of collision, which is increased beside the existing Vessel Traffic System (VTS). The paper discusses the synthesis early warning system, or automatic crossing supervisor for Singapore Strait by using the Timed Petri Nets (TPN). Authors proposes dividing the strait in zones, so called crossings, where routes are crossing and in which the number of ships must be limited. The maximum number of vessels in period of time of the highest traffic density through the crossings are determined. Derived constraints are used for synthesis of crossing supervisor. The authors uses Petri nets to make model Singapore Strait, and use P-invariant method to syntheses crossing supervisor, which limits the number of ships in all critical crossings. Finally, the author verified derived supervisor by using *Visual Object Net* ++ programme for computer simulation. With the aid of *Transas* nautical simulator, the traffic in the strait is analysed.

Keywords: maritime transport, safety, Singapore Strait, supervisor, Petri net, simulation, vessel traffic system.

Notations

AIS – automatic identification system;
ARPA – automatic radar plotting aid;
C – control place;
CTSPN – composite traffic system Petri net;
DES – discrete event system;
EA – evolutionary algorithms;
EBG – eastern boarding ground;
ECDIS – electronic chart display information system;
EPD – electronic prototype display;
IBS – integrated bridge system;
IMO – international maritime organization;
MPA – marine port authority;
NTPRO – nautical *Transas* professional;
P – route priority;
S – sector;
STCC – shore traffic control centre;
TPN – timed Petri net;
TSPN – traffic system Petri net;
TSS – traffic separation schemes;
UKC – under keel clearance;
VTIS – vessel traffic information system;
VTS – vessel traffic system;
W – route importance.

Introduction

The safety of maritime traffic is influenced by a number of factors that may, to a certain extent, affect the safety of vessels, people, property and environment. These factors may result in dangerous situations, such as grounding, collision, fire, capsizing, main engine failure, hull damage, pollution and other events. The drawbacks of the existing safety systems and technologies applied in the sea traffic appear especially in seaway nodes, with reduced passage and increased traffic.

There are two approaches that can be used to avoid collision. The collision avoidance problem can be solved by using software in IBS. In the paper (Lazarowska 2014) a new approach for an intelligent obstacle detection and avoidance system on board ship is presented. Second, collision prevention problem can be solved by using application in VTS centres software. Methodology with EA presented in the paper (Szlapczynski 2013) has been used to search an optimal set of safe trajectories in the area of TSS that include detecting and penalizing TSS violations.

Research from the web (MPA Singapore 2019; Singapore DOS 2019) also deals with the potential collision risks and possibilities of enhancing the safety of naviga-

tion by using software tools applied to the specific area of the Singapore Strait. Approach in this article is also collision prevention problem, and it is proposed a new application in VTS centre, so called supervisor. The authors propose a supervisor that monitor traffic in predefined routes in the sectors, and warns a VTS operator in case of TSS violation.

Similar problems has been researched within projects: *EfficienSea*, *AccSeas* and *MonaLisa* project, which are being carried out in the area of Baltic and Nord Sea. The main aim for *EfficienSea* project is to provide planned route for vessel (Porathe *et al.* 2013), the aim for *AccSeas* project is tactical exchange of route between ship and shore, which partly relies on the issue of this article (Alexander *et al.* 2013). The *MonaLisa* project has related within synthesis of supervisor in risky area and main scope of this project is examination UKC for particular vessel and prohibited area on vessel planned route for vessel, which are in vicinity of STCCs. Ultimate goal of this project is to build in STCCs functionality check for UKC and prohibited area (no-go area) and exchange of planned voyage between ECDIS and centres, which are controlling traffic (NSHC 2012). In this article research studies is based on enhancing collision prevention in the area of restricted manoeuvring. In this area it is not possible to change routes significantly. The only way is to alert ships to slow down or to minimally change the course. So authors proposes implementation of early warning computer based supervisor in the VTS centres, which on time alerts VTS operator in case of irregular traffic situations.

The article (Kao *et al.* 2007) use fuzzy logic methodology to enhance the VTS operator's decision-making abilities by providing a collision avoidance alert system. The authors define guarding ring around every ship. The VTS software calculates radius of guarding ring for every ship by analysing three input variables – length of ship size L, speed V and sea state S. Then, VTS software calculate danger index D between every pair of ships, which is proportional to the variation of strait distance and slope of the radical axis of two circles. Approach in this article is similar to the approach of Kao *et al.* (2007) in the sense that the VTS centre needs to be upgraded with additional alert software for collision avoidance. But, the approach of Kao *et al.* (2007) is more convenient for wider sea area compare to narrow area in case of dense traffic. In that case the VTS operator would face simultaneously with high danger indexes and with higher risk of collision.

Contribution and novelty of our approach is that we suggest division of VTS surveillance area in small sectors, in which VTS operator can restrict number of ships, and also control priority of entrance into the sector. The method proposed by Kao *et al.* (2007) can be used for collision avoidance only in combination with method proposed in this article for narrow strait.

The suggested supervisor system restricts the vessel movement in the sectors, i.e. the smallest spatial units accommodating one vessel each, and coordinates the transit of vessels in the traffic nodes only in case of increased collision risk. The suggested solutions are in line with the requirements and guidelines of the IMO for the implementation of modern safety systems such as e-navigation.

The supervisory system controls the maritime traffic by using Petri nets (Murata 1989; Wang 1998) and the mathematical method of P-invariants (Harušťák, Hrúz 2000; Kezić *et al.* 2006; Yamalidou *et al.* 1996). MATLAB (*https://se.mathworks.com*) programming language has been used for the synthesis of the supervisory system, while the verification of the supervisory system has been performed by using computer-supported simulation and *Visual Object Net ++* (Drath 2019).

Research studies is carried out in four phases:

- *first phase* of conducted research is discretization of traffic system on sectors by program (*Model Wizard version 6.0*) where the vessels navigating;
- *second phase* of conducted research is defining fixed routes where the vessels navigating by *Transas* nautical simulator (*Transas NTPRO version 5.35*);
- *third phase* is modelling of traffic process by using TPN tools;
- *fourth phase* is synthesis of surveillance system using MATLAB tools for calculating number of control places in TPN.

Verification of proposed supervisor is carried out on computer simulation on example of Singapore Strait.

1. Analysis of marine traffic in Singapore Strait

The Singapore Strait is a 105 km long, 16 km wide shipping channel between the South China Sea and the Malacca Strait (Weng *et al.* 2012). It is divided into three zones: VTIS East, VTIS Central and VTIS West. The area discussed in this paper lies in the middle of the Singapore Strait (VTIS Central), where the flow of the vessels in transit is intersected by the flow of vessels crossing the traffic separation zone. The traffic is controlled by STCC that belongs to the VTIS Central. The average daily traffic flow amounts to 300 vessels, i.e. about 100000 vessels per year (StrasseLink 2017). 80% of crude oil for the North-Eastern Asian destinations and 1/3 of the global sea-borne cargo pass through the Singapore Strait, making it one of the busiest routes in the world. The case study refers to the Singapore Pilot Eastern Boarding Ground "A" and the Pilot Eastern Boarding Ground "B". Figure 1 (StrasseLink 2017) shows traffic density in the area as presented by the *Transas* nautical simulator (*Transas NTPRO version 5.35*).

This area prevailing with dry and liquid cargo carriers (Table 1), which travel in transit, cross the traffic separation zone, and enter the port area. When such crossings occur, the shore-based VTS supervises the vessels and warns them of the potential risks such as dangerous proximity, collision situation, etc. Key participants involved in this activity are the ship master, the maritime pilots, the tug masters and VTS operators (Mansson *et al.* 2017).

The types of vessels passing through the strait are shown in Table 1 (SCM 2014).

Figure 1. Traffic density in the Singapore Strait area

Table 1. Amount of vessels in the Singapore Strait
per year and per type of vessel

Type of vessel \ Year	2009	2010	2011	2012	2013	2014
VLCC/Deep draft	4221	4333	4539	4732	4825	5225
Tanker vessel	16398	16247	16233	17345	18296	19335
LNG carrier	3330	3579	3830	4014	4248	4658
Cargo vessel	8560	8445	7996	7950	7613	7126
Container vessel	22310	24806	25552	24639	24658	24615
Bulk carrier	11186	11642	10851	11678	12658	12695
Ro-ro	2394	2624	2545	2980	2998	3194
Passenger vessel	1250	1071	877	861	1063	1169
Livestock carrier	43	45	47	38	55	31
Tug/Tow boat	598	545	414	529	563	855
Government vessel	67	37	57	50	58	25
Fishing vessel	61	20	20	52	27	135
Other	941	739	577	609	911	991
Total	71359	74133	73538	75477	77973	80055

The sea accidents taking place in the Singapore Strait include ship collisions and contacts, groundings, fires, main engine failures (loss of propulsion), various pollutions of the environment, etc. Due to the constant annual increase in traffic, the situation is getting more and more serious, as the existing traffic regulation is unable to ensure the same or higher level of safety for the increasing number of vessels. One of the introduced novelties requires the vessels to carry three green lights when crossing the separation zones or entering/leaving the port. However, the practice has confirmed that neither the new requirements nor the standard coordination between VTS operators and ships reduce the accident probability. Various levels of navigational decision-making or control can be distinguish (Pietrzykowski *et al.* 2017). The statistics about sea accidents (Singapore DOS 2019):

– 55% collisions;
– 13% fires and explosions;
– 8% machinery damage and failures;
– 13% missing vessels (disappeared under unknown circumstances);
– 8% wrecks and groundings.

Shore-based centres for the supervision and management of sea traffic so called STCC have been established in order to minimise the risk of collision and other accidents in busy navigation areas such as the Singapore Strait. However, these centres should be equipped with the automatic alert supervisory systems when the number of crossing vessels becomes excessive.

This study discusses the synthesis of the supervisory system, i.e. the "early alert" system that automatically warns the operator of the errors in ship manoeuvring. In order to carry out the synthesis of the supervisory system, the supervised area is divided into sectors, and the vessel movement is modelled as a set of discrete events.

Figure 2 presents a block diagram of the STCC centre equipped with the synthesised supervisory system, and also presents the flow of information that is gathered by devices forming an STCC (ARPA, ECDIS and AIS) and is transferred to the STCC operator, STCC supervisory system, and EPD (is an option featuring the display of other vessels' routes on the electronic display fitted next to the electronic chart) displays ashore and on board the vessels sailing through the supervised area.

The size of the sector can be defined empirically, i.e. by the shore-based STCC operator who controls the movement of vessels in accordance with the traffic flow, type of vessels and type of cargo they convey. The type of vessels affects the sector's size because the vessels of the same length may vary in draught up to ten metres, and this should be taken into consideration when determining the size of a sector. Furthermore, the size and the shape of the sector depend on the number of special-purpose craft in a specific area: dredgers, heavy-lift vessels, research vessels, cable-laying vessels, and the like.

Input data on conditions and events are gathered from the on-board devices such as ARPA, ECDIS and AIS. The supervisory system uses these input data for defining the possibility of collision on the basis of discrete events. The supervisory system selects dangerous situations and sends out warnings – alerts to the STCC operators, e.g. on the number of vessels that is higher than allowed in an individual sector. Taking the received information into consideration, the operator takes necessary measures by applying the shore-to-ship communication system and warning the officer of the watch or the master. In addition to selecting dangerous events and giving warnings to vessels, the supervisory system provides the following information about:

– traffic density in the sector;
– priorities given to vessels (vessel 1, 2, 3, ..., *n* may have the priority in the crossing situation);
– duration of the overcapacity of the individual sectors.
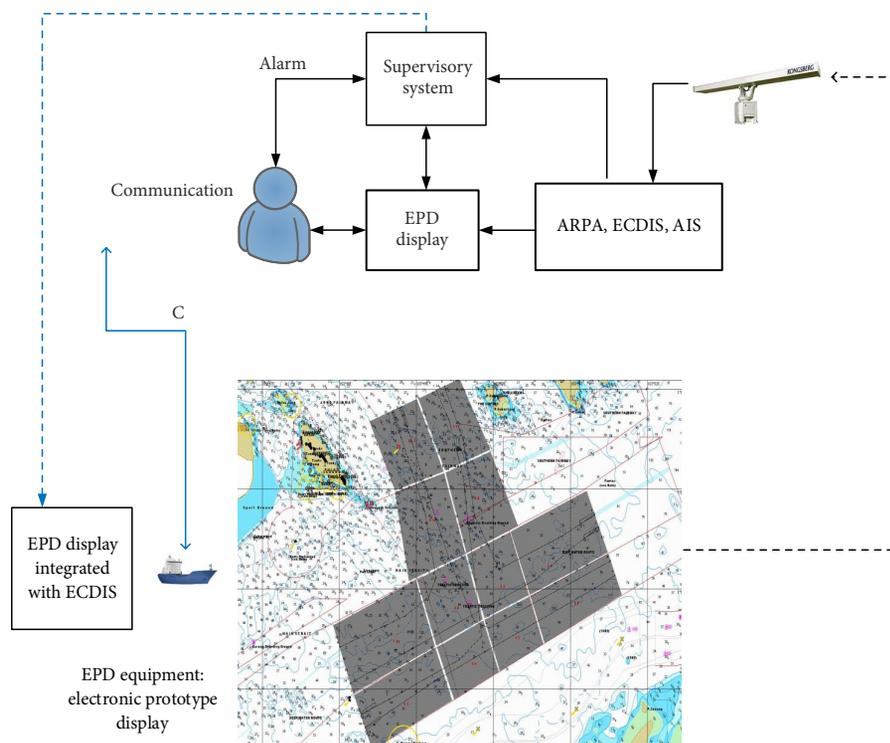
Figure 2. Proposal for the vessel traffic management system

All data are graphically presented on the EPD display fitted both to the vessel and the shore-based centre. Correct operation of the supervisory system requires the STCC operator to enter the pre-defined fixed shipping routes and to define priorities and other relevant factors for each route entering the supervised area. The STCC then sends the predefined/fixed shipping routes to the vessels. The routes are displayed on the vessel's EPD that is integrated with the ECDIS device. The vessel, which obtains a route allocated on the EPD display has to accept and follow the route (Porathe *et al.* 2014). The STCC assigns the priority and importance to each shipping route passing through the sector. Priorities are assigned as numerical values (1, 2 and 3, ...). The route of higher priority (P = 3) enters the crossing before the route of lesser priority (P = 2 or P = 1). The levels of importance of the routes W are also numerical values (1, 2 and 3, …) that the operator assigns to every shipping route that enters the supervised area. The supervisory system makes sure that a limited number of the very important vessels are in the same sector at the same time. For instance, if the same crossing is approached by the military vessel and the bulk carrier, both having the route of the same priority of passage P = 2 because both of them have to reach the same pilot boarding station at the same time, the high importance value W = 2 is allocated to the military vessel due to safety reasons, which implies that no other vessel is allowed to enter the sector until the military vessels leaves it. The supervisory system blocks the entrance of any other vessel as long as the military vessel is within the sector. The suggested synthesised supervisory system of

the STCC centre automatically warns the operator if a vessel does not comply with the allocated route or if certain vessels have to pause before entering some crossings. If the alert is sounded, the operator establishes the shore-to-ship communication and warns the concerned vessel.

2. Methodology for collision supervisor design by using Petri net

The statistics (Table 1) clearly suggests that one of the possible way to ensure safe traffic flow in the strait is to introduce a crossing supervisor system that would detect, as this paper describes, any increased density of crossing vessels and assist the VTS operator in traffic coordination. Present technology in Singapore Strait has ability to predict and alert dangerous situation, however there is no automatically solution and orders from one place, which could give advice to avoid dangerous situation. Too many different actors included in this situation (officers who command vessels) might give different conclusions and solutions using different methodology and on such way increase possibility of human error. Therefore, one central place, which might give orders using one methodology is needed.

In this paper, authors use Petri net methodology for design collision prevention supervisor in the narrow straits traffic area.

Petri nets and the method of P-invariants are tools, which are essential in the process of the supervisory system synthesizing. The marine channel traffic system can generally be described as a DES. This study makes use of

the Petri nets, a well-known tool for DES, to model the vessel traffic system. The Petri net is a 6-tuple (Murata 1989):

$$Q = (P, T, I, O, w, m_0), \tag{1}$$

where: $P = \{p_1, p_2, \ldots, p_n\}$ – set of places; $T = \{t_1, t_2, \ldots, t_n\}$ – set of transition; $I : P \times T \rightarrow \{0, 1\}$ – input function; $O : T \times P \rightarrow \{0, 1\}$ – output function; $w : (I, O) \rightarrow \{1, 2, 3, \ldots\}$ – weight function; m_0 – initial marking.

Places and transitions $v \in P \cup T$ are called nodes and denote states and events in the DES. Given any node v, let $\cdot v$ and $v \cdot$ respectively denote the pre-set and post-set of v in usual way, i.e. the set of nodes that have arcs to and from v, respectively. An available resource or ongoing ships in DES is indicated by tokens in respective places. A transition $t \in T$ is enabled at a marking $m(p)$ if $\forall p \in \cdot t$, $m(p) \geq w$ ($\cdot t$ is a set of input places to transition t). A transition t that meets the enabled condition is free to fire. When a transition t fires, all of its input places lose a number of tokens, and all of its output places gain a number of tokens. The state of Petri net changes from marking $m_k(p)$ to marking $m_{k+1}(p)$:

$$m_{k+1}(p) - m_k(p) + A^T \cdot \sigma, \tag{2}$$

where: A – incidence matrix; σ – firing vector.

The incidence matrix A consists of rows (places) and columns (transitions), describing the way the places and transitions are interconnected by the arcs in the Petri net. The firing vector σ defines the transitions that fire when the net state changes. The tree of the available states (called reachability tree) contains all possible net states appearing after firing all the transitions. The structural characteristics of the Petri net are P-invariant. The P-invariant corresponds to set of places whose weighted token count remains a constant for all possible markings. The P-invariant X can be found by solving the equation:

$$x^T \cdot A = 0, \tag{3}$$

where: x – is a n dimensional positive integer vector whose elements mark the places in the Petri net.

The goal of this paper is to model the traffic system by using Petri net method, and to compute the supervisor, which restricts the set of all states in the net to the set of allowable states. The calculation of the supervisor begins with defining the set of constraints to the Petri net model in the form of mathematical equations:

$$\sum_{i=1}^{n_c} l_i \cdot m(p_i) + m(c_0) = \beta, \tag{4}$$

where: $m(p_i)$ – marking of the place p; l_i, β – integer constants; $m(c_0)$ – marking of the control place c_0; n_c – number of constraints.

By converting the equation into matrix form, it is possible to calculate the supervisor incidence matrix, which defines all control places and connections between those places and transitions in the Petri net model, as well as the initial marking of the supervisor (Kezić *et al.* 2005, 2006):

$$A_c = -L \cdot A_p; \tag{5}$$

$$m_{c_0} = b - L \cdot m_{p_0}, \tag{6}$$

where: A_p – incidence matrix of the Petri net, which model the process; m_{c_0} – initial marking of the supervisor; m_{p_0} – initial marking of the Petri net, which model the process; L – constraints matrix; b – capacity vector.

The pilot station EBG has been shown in Figure 3. The area of the Singapore waterway is divided into sectors. The overall number of sectors in the supervised area shown in Figure 3 amounts to 12 sectors that are marked as S1, S2, S3, S4, S5, S6, S7, S8, S9, S10, S11 and S12. The vessels travel through the channel using 6 fixed, predefined routes. The route R1 passes through sectors S1, S2, S9 and S11, the route R2 through sectors S1, S2, S3 and S4, while the route R3 passes through sectors S5, S6, S7, S2, S9 and S11. The route R4 passes through sectors S5, S6, S7 and S8, the route R5 through sectors S12, S10 and S4, while the route R6 passes through the sectors S12, S10, S3, S6, S7 and S8. Sectors S2, S3, S6 and S7 are called crossings as the shipping routes intersect there. All sectors and routes are defined by the STCC operator. The analysis of the simulation has been performed with the aid of the *Transas* nautical simulator (*Transas NTPRO version 5.35*) for the heaviest possible traffic in 6 fixed routes at fixed vessel speed. Each route has 20 vessels that pass through sectors. If there are unmanned ships, which are recommended in the near future, there is a need to apply automatic system, which coordinates ships moving in crossing area. Based on this has to be considered the maximum number of ships in critical sectors (in this article are S2, S3, S6 and S7). Also, have to be considered the priority of entrance and importance of ships in crossing zone. Here is simulated the maximum traffic flow in the Singapore region (particularly "high risk collision area" in EBG A or B) on the *Transas* nautical simulator (*Transas NTPRO version 5.35*), and have proposed design of automatic supervisor for this particular case (Figure 2) using Petri net formalism. This supervisor contains a number of constraints, which are defined by STCC operator, and the supervisor monitors the traffic and automatically warns operator in the case of constraints violation.

It has been found out that the area presented in Figure 3 copes with a heavy traffic in the route crossings. The simulation included ten vessels sailing from their starting positions at the same time, at the fixed speed of 10…12 knots, into the limited capacity of the sectors S1, S8, S4, S5, S9, S11, S10 and S12. The sectors are plotted in the nautical simulator by using *Model Wizard version 6.0* program. Times of entrances and exits of the vessels for each individual sector were measured. The obtained times were inserted into the Petri net model of the traffic system – TSPN. TSPN can be derived from CTSPN (Figure 8) by removing control places C2, C3 C6 and C7. The simulation of this Petri net has produced the graphs. A threatening, large number of vessels can be clearly noted in certain crossings.
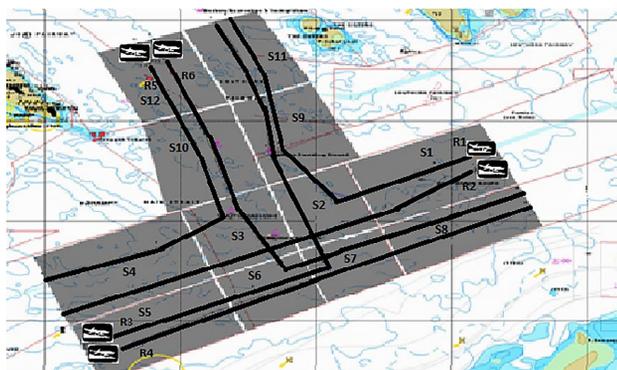
Figure 3. Sectors within the Singapore Strait

3. Simulation and results

Synthesis of the supervisory system provides a synthesis of the TSPN and CTSPN of the Singapore Strait. The synthesis is performed with the aid of time Petri nets while the simulation is carried out by using *Visual Object Net ++* software (Drath 2019). The traffic process in the Singapore Strait can be modelled as a Petri net with a certain set of conditions. However, some of the condition can be forbidden (for example, too many ships in crossing), and the set of all possible reachable states must be reduced to the set of allowable states. To reduce the set of reachable states (Kezić *et al.* 2006) of TSPN to the set of allowable states, the supervisor can be modelled in the form of additional control places must be added to the TSPN. The set of allowable states are defined by the constraints to TSPN. Each constraint to TSPN produces 1 control place, which forms a P-invariant with the particular set of TSPN places. The set of all control places forms the supervisor. TSPN, together with the control places forms the CTSPN. The synthesis of the crossing supervisor is started by defining and synthesising the TSPN Petri net, according to the following steps. The first step refers to defining the TSPN that models the Singapore Strait. This involves the definitions of sectors, fixed routes, capacities of individual sectors Krs, and crossing times within the net. The TSPN net, as stated above, can be observed in Figure 8, without the supervisor consisting of the control places C1, C2, C3 and C4 and the associated arcs connecting the control points with the crossings. Then, the computer simulation of the TSPN net is performed with the aid of the simulation programme *Visual Object Net ++*, provided that the heaviest possible traffic is assumed (twenty vessels entering simultaneously into all predefined routes in the supervised area). The traffic in critical crossings is observed and the allowed number of vessels is determined through the computer simulation. The Figures 4–7 show results of simulation in critical sectors S3, S2, S6 and S7 presenting the minimum and maximum number of ships at certain intervals.

Figure 4 shows the number of vessels in sector S3. The duration of the simulation is 145 min, and the maximum number of vessels appearing simultaneously in sector S3 are five vessels in the interval from the 85…101 min.

Figure 5 shows the number of vessels as the time function in sector S2. The duration of the simulation is 150 min, and the maximum number of vessels appearing simultaneously in sector S2 is four vessels in the interval from the 96…100 min.

Figure 6 shows the number of vessels in sector S6. The duration of the simulation is 145 min, and the maximum number of vessels appearing simultaneously in sector S6 is four vessels in the interval from the 98…113 min.

Figure 7 shows the number of vessels in sector S7. The duration of the simulation is 145 min, and the maximum number of vessels appearing simultaneously in sector S7 is four vessels in two intervals. The first interval is from the 65…83 min, while the second interval extends from the 100…130 min. All the obtained graphs (Figures 4–7) present the number of vessels in critical sectors, i.e. the sectors where the crossings of shipping routes take place. The number of vessels is obtained through the simulation of the traffic flow as shown in Figure 3. The graphs show that crossings S2, S3, S6 and S7 contains 4…5 vessels. The simulation shows that the number of vessels in crossings is too high, so that number of vessels for each crossing has to be limited. The synthesis of the supervisor will automatically alert the traffic overflow in the crossings where the traffic is shown. Previous simulations has shown that so many ships in critical sectors lead to increased collision situation and in some cases to collision. Based on the above, it is considered necessary to introduce control points for the critical sectors and to carry out the appropriate simulations, which results are shown in the Figures 9–12.
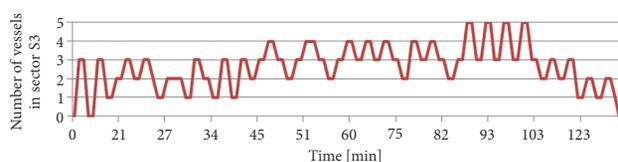
Figure 4. Number of crossing vessels in sector S3
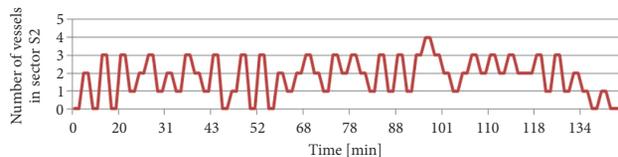
Figure 5. Number of crossing vessels in sector S2
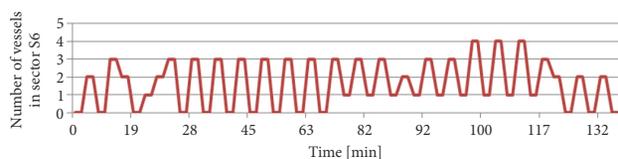
Figure 6. Number of crossing vessels in sector S6
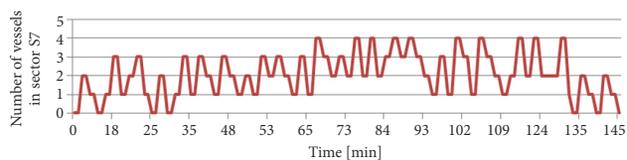
Figure 7. Number of crossing vessels in sector S7

4. Collision prevention supervisor synthesis and simulation

According to the results produced by the simulation, it can be concluded that a large number of vessels may appear in these sectors. Given the sailing area and the sector size, this might present a potentially high risk for the safety of navigation, so that it is necessary to impose constraints with the purpose of allowing maximum two vessels in one crossing at the same time. The constraints on the number of vessels (Bordbar *et al.* 2014; Li, Wonham 1993) are required because a larger number of vessels in narrow crossings might result in near-miss situations and collisions. It should be noted that the STCC operator can alter the constraints on line in accordance with the actual traffic flow. The constraints on the maximum allowed crossing capacity $K_{cr} \leq 2$ can be formulated in a mathematical way, as follows:

$$K_{cr} = m_{R4P4} + m_{R3P4} + m_{R6P6} \leq 2; \quad (7)$$

$$K_{cr} = m_{R2P3} + m_{R1P3} + m_{R3P5} \leq 2; \quad (8)$$

$$K_{cr} = m_{R2P4} + m_{R6P4} + m_{R5P4} \leq 2; \quad (9)$$

$$K_{cr} = m_{R3P3} + m_{R4P3} + m_{R6P5} \leq 2, \quad (10)$$

where: m present places, for example (Figure 8), m_{R6P5} – m is place P5 on route R6, etc.

Relation (7) represents the constraint for sector S7, relation (8) for sector S2, relation (9) for sector S3, while relation (10) represents the constraint for sector S6. By applying the P-invariant method, the CTSPN shown in Figure 8 is calculated. The CTSPN net models the TSPN with crossing supervisor that consists of four control places: C2, C3, C6 and C7. Control place C2 limits the number of vessels in sector S2, place C3 limits the number of vessels in sector S3, place C6 does the same in sector S6 while C7 limits the number of vessels in sector S7. The control places, along with the places belonging to these sectors, form the P-invariant. The task of the control places is to restrict the number of tokens with regard to relations from (7) to (10). The CTSPN shows an algorithm of the functioning of the supervisory system, and can be easily transferred into the appropriate computer code.

The computer simulation of the CTSPN net produces the graphs shown in Figures 9–12. The graphs shows the number of vessels in crossings S2, S3, S6 and S7, where the traffic density without the supervisor's was four to five vessels. The control places (the crossing supervisor) in the Petri net restrict the number of vessels in the individual sectors. The results presented in Figure 9 show that the largest number of vessels in sector S6 does not exceed two vessels,
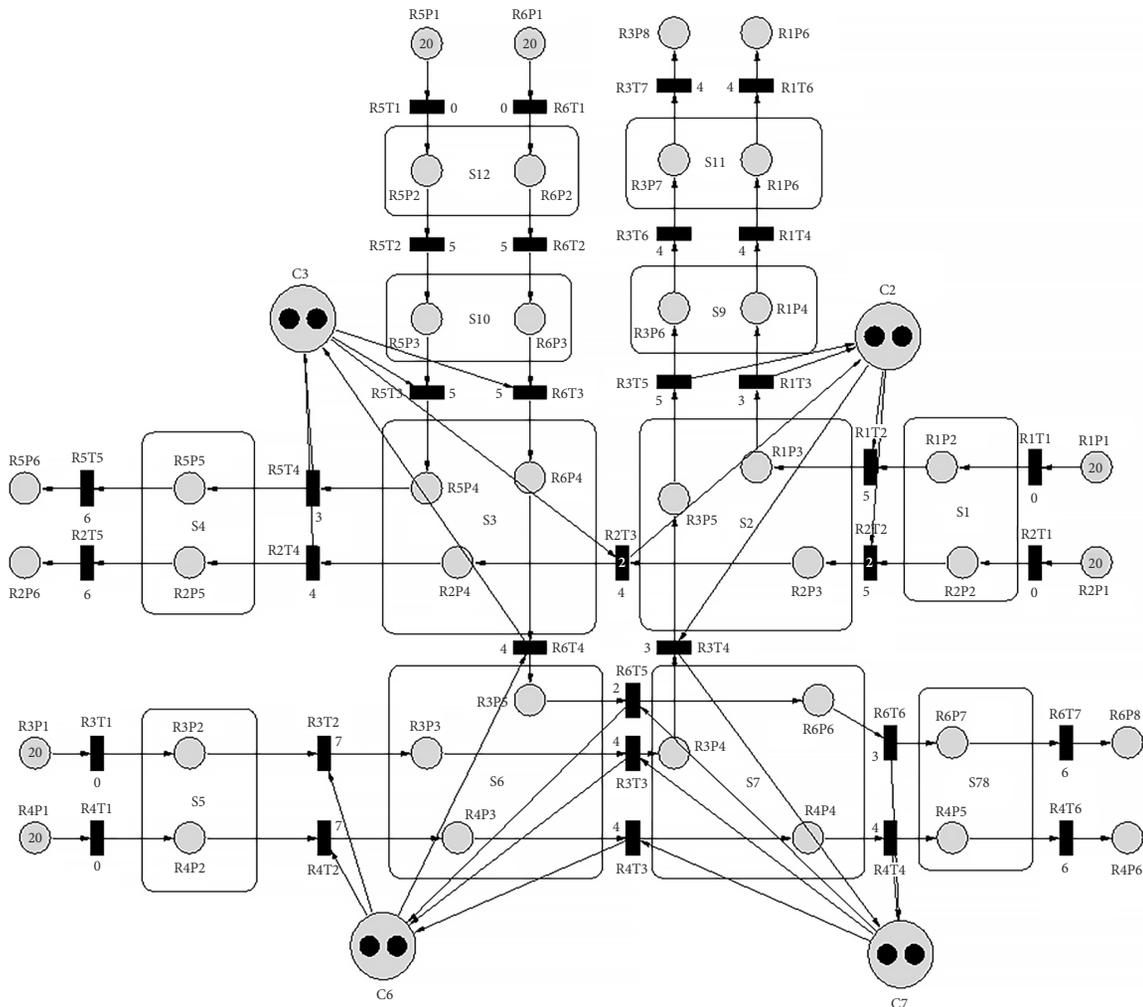
Figure 8. TSPN and CTSPN of the traffic in the Singapore Strait

and it can be concluded that the control place C6 does not allow more than two vessels in the Petri net with control places in sector S6.

The simulation results presented in Figure 10 show that the largest number of vessels in sector S3 does not exceed two vessels, and it can be concluded that the control place C3 does not allow more than two vessels in the Petri net with control points in sector S3.

The results presented in Figure 11 show that the largest number of vessels in sector S2 does not exceed two vessels, and it can be concluded that the control place C2 does not allow more than two vessels in the Petri net with control points in sector S2.

The simulation results presented in Figure 12 show that the largest number of vessels in sector S7 does not exceed two vessels, and it can be concluded that the control place C7 does not allow more than two vessels in the Petri net with control points in sector S7.

It is obvious that the number of vessels in the crossings does not exceed the imposed limits, i.e. there are no sectors with more than two vessels present at the crossings at the same time. The presented diagrams indicate the times needed for all vessels to pass through the sectors: S3 = 270 min, S6 = 275 min, S2 = 245 min and S7 = 280 min, naturally, the drawback of the supervisory system is that the traffic flow has to be restricted and, consequently, the duration of passage prolonged, in order to increase the safety of navigation. This is evident when comparing Figures 4–7 and Figures 9–12. These comparisons confirm that the implementation of the restrictions in the supervisory system slows down the flow of sea traffic, mainly depending on the length of the route and the vessels' final destinations. Comparisons of the duration of passage through the sectors (crossings), with and without the crossing supervisor, lead to the conclusion that the differences in the duration of passages for the sectors S2, S3, S6 and S7 are: ΔS2 = 95 min, ΔS3 = 125 min, ΔS6 = 130 min, ΔS7 = 135 min.
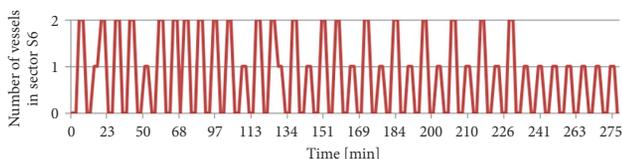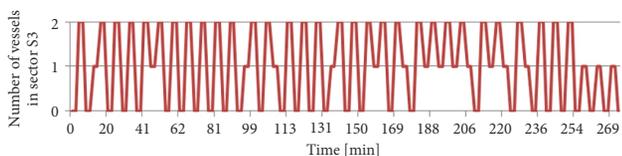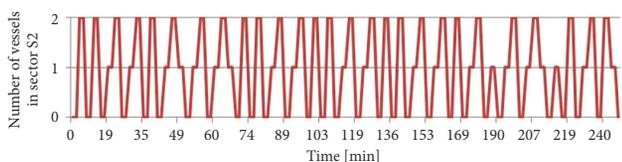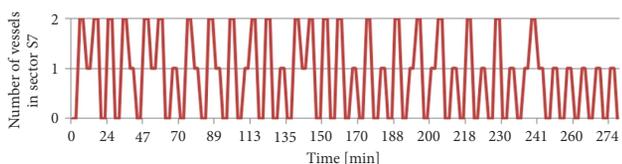
There is set of procedure for developing TPN and there is a new methodology developed in a new research studies regarding crossing of predefined routes in defined sectors (Figure 3). Novelty can be consider as upgrade of new supervisory system providing following information's as: traffic density, priorities (vessel $P = 1$; $P = 2$ and $P = 3$, which is highest level for priority). Contribution and novelty is presented by division of VTS on surveillance area in small sectors, where VTS operator can restrict number of ships, and also to control priority of entrance into the sector by implementing defined control places.

Conclusions

This article suggests an automated supervisory system for early warning, which should be installed to the maritime traffic control centres in order to significantly enhance the safety of navigation. The suggested supervisory system would ensure the compliance with the restrictions regarding the number of vessels simultaneously passing through the crossings, priorities when entering the sectors, and individual vessel's level of importance. A new method has been suggested for the synthesis of the supervisory system through the application of time Petri nets and P-invariant method. The paper describes the methodology of the supervisor synthesis on the case study of the Singapore Strait. The Petri net of the Singapore Strait has been modelled and the simulation of the traffic flow has been carried out. The model of Singapore Strait comprises the definition of six allowed shipping routes. The routes pass through eight sectors having no crossings and four sectors with route crossings. The simulations involved the real speed of the vessels and the real size of the sectors. The durations of passage have been calculated with the aid of the *Transas* nautical simulator (*Transas NTPRO version 5.35*). After designing TSPN of the Singapore Strait, the real times of the passages of the vessels through the sectors are entered into the model, and the simulation of the maximum traffic flow through the crossings under the agreed conditions (twenty vessels travelling on each route at fixed, defined speed) is carried out. The simulation results indicate that there are up to five vessels in these crossings in the same time, which is not acceptable. This means that the existing limit of two tokens per place is not a solution to the problem. The only way to reduce the risk of collision is to implement a system that automatically supervises the entrance of vessels into the crossings and

Figure 9. Number of crossing vessels in sector S6

Figure 10. Number of crossing vessels in sector S3

Figure 11. Number of crossing vessels in sector S2

Figure 12. Number of crossing vessels in sector S7

their exits. Reducing of the number of vessels in crossings can be achieved by warning the participants in the sea traffic to necessary correction of vessel's speed when approaching the occupied sectors. By restricting the number of tokens in crossing area to two tokens, the method of P-invariant synthesizes the crossing supervisor, which consists of four control places. These control places must be added to TSPN to achieve CTSPN of the Singapore Strait. The simulation of CTPSN indicates that a maximum of two vessels is present in the crossing sectors at the same time. The crossing supervisor has been verified by this procedure. Comparing the passage duration with and without the crossing supervisor, it can be concluded that the crossing supervisory system slows down the traffic flow to a certain extent, but the increase in the safety of navigation due to the restriction on the number of vessels in crossings is evident.

Relatively large traffic in Singapore's Straits makes this passage a bottleneck on transpacific route. Existing traffic control and control of traffic systems are only partial solutions that will within further increasing traffic become insufficient. Therefore, a supervisory system solution is proposed that takes into account the time passage through the sector and the sequence of sectors through the ships are passing. The calculation of these parameters should be a scenario of one (central) system and not more (ships) systems in order to reduce the possible error. The current solutions (projects) provide reliability but the infrastructure of such solutions is much more complex and more expensive. The solution proposed by the supervisor is reliable and relatively inexpensive and no special preparation activity are required for its application. Proposed methodology is suitable for other global strait worldwide and particularly in narrow strait such as Gibraltar Strait, Dover Strait, approaching to narrow channels etc. Recent accidents in these areas are new aim to continue various research studies regarding this problem. In future research, the authors will concentrate on synthesis of crossing collision prevention supervisor using Colour Petri net as simulation tool, which provide simulation of more complex systems.

Author contributions

Rino Bošnjak was responsible for the main aim of this study research and wrote the first draft of the article.

Danko Kezić and Zvonko Kavran were responsible for the designing and developing model by using Petri nets.

Pero Vidan was responsible for data interpretation.

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