ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

ASSOCIATION RULE MINING FOR IDENTIFYING FACTORS IN DYNAMIC POSITIONING INCIDENTS AND ACCIDENTS

Ph.D. THESIS

Tuğfan ŞAHİN

Department of Maritime Transportation Engineering

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JANUARY 2024

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

DİNAMİK KONUMLANDIRMA KAZALARINA AİT FAKTÖRLERİN BİRLİKTELİK KURAL MADENCİLİĞİ İLE TANIMLANMASI

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Tuğfan Şahin, a Ph.D. student of ITU Graduate School student ID 512182006, successfully defended the thesis/dissertation entitled "ASSOCIATION RULE MINING FOR IDENTIFYING FACTORS IN DYNAMIC POSITIONING INCIDENTS AND ACCIDENTS", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To all seafarers who lost their lives at sea,

FOREWORD

The history of marine safety is indelibly marked by both triumphs and tragedies. As Robert Frump aptly notes in “Until the sea shall set them free” meaningful changes in maritime safety often emerge in the aftermath of disasters.

Marine accidents have always been of vital importance to the industry because the lessons learned from them typically lead to the establishment of new rules or upcoming regulations. This truth is particularly evident in dynamic positioning (DP) incidents, which, due to the nature of offshore operations, can have catastrophic consequences.

The initial introduction of the dynamic positioning system occurred in the early 1960s, credited to Howard Shatto, widely recognised as the progenitor of this technology. The Euroka drillship, the world’s first DP-installed vessel, marked a milestone in dynamic positioning. With the vessels controlled meter by meter during operations, the consequences of DP incidents pose a considerable risk to both human life and the environment, a concern exacerbated by the surge in projects and DP-equipped vessels after the year 2000. Consequently, the safety of operations and the prevention of DP incidents became more significant in the offshore industry.

This Ph.D. thesis is prepared to investigate the underlying factors contributing to dynamic positioning incidents, aiming to propose measures that will enhance the safety of DP operations and prevent similar incidents in the future.

I express my profound gratitude to my esteemed advisor, Associate Professor Dr. Pelin Bolat, for her unwavering assistance and guidance throughout my academic pursuit and the development of this thesis. Whenever needed, she provided me with a light to clearly show my route.

I extend special gratitude to the International Maritime Contractors’ Association for their support in providing annual DP incident reports, a pivotal contribution to the success of this thesis. I am also thankful to those, whose names may have escaped mention, for their support through articles and questionnaires.

All figures (images, photographs, and graphics), tables, and texts within this thesis belong to the author, unless otherwise indicated.

December 2023

Tugfan SAHIN
(Oceangoing Chief Officer &
Unlimited DPO)

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ABBREVIATIONS

ABS	: American Bureau of Shipping
ACTA	: Applied Cognitive Task Analysis
AHTS	: Anchor Handling Tug Supply
ANP	: Analytical Network Process
API	: Application Programming Interface
ARM	: Association Rule Mining
ASOG	: Activity Specific Operating Guidelines
AVR	: Automatic Voltage Regulator
BN	: Bayesian Network
BTM	: Bridge Team Management
CAMO	: Critical Activity Mode
CMF	: Common Mode Failure
CPP	: Controllable Pitch Propeller
DGPS	: Differential Global Positioning System
DNV	: Det Norske Veritas
DP	: Dynamic Positioning
DPACSS	: Dynamic Positioning Accreditation and Certification Scheme Standard
DPC	: Dynamic Positioning Committee
DPO	: Dynamic Positioning Operator
DPS	: Dynamic Positioning System
DPTEG	: Dynamic Positioning Training Executive Group
DSV	: Diving Support Vessel
ERO	: Engine Room Operator
ETA	: Event Tree Analysis
ETO	: Electro Technical Officer
FMEA	: Failure Mode and Effect Analyses
FPP	: Fixed Pitch Propeller
FPSO	: Floating Production Storage and Offloading
FSA	: Formal Safety Assessment
FSRU	: Floating Storage and Re-gasification Unit

GLONASS: Global Navigation Satellite System
GPS : Global Positioning System
HFACS : Human Factor Analysis and Classification System
HIPAP : High Precision Acoustic Positioning System
HMI : Human Machine Interface
HPR : Hydro-acoustic Position Reference
IADC : International Association of Drilling Contractors
ICS : International Chamber of Shipping
IFAC : International Federation of Automatic Control
IFIP : International Federation for Information Processing
IMO : International Maritime Organization
IMCA : International Maritime Contractors' Association
IMR : Inspection, Maintenance, Repair Vessel
ISOA : International Support Vessels Owners' Association
I/O : Input/output
KR : Korean Register
LAN : Local Area Network
LBL : Long Base Line
LoP : Loss of Position
LoR : Loss of Redundancy
LR : Lloyd's Register
MDO : Marine Diesel Oil
MGO : Marine Gas Oil
MODU : Mobile Offshore Drilling Unit
MPSV : Multi-Purpose Supply/Support Vessel
MRU : Motion Reference Unit
MSC : Maritime Safety Committee
MTO : Man, Technology and Organization
NCS : Norwegian Continental Shelf
NI : The Nautical Institute
OCIMF : Oil Companies International Marine Forum
OCV : Offshore Construction Vessel
OSV : Offshore Support/Supply Vessel
OSVDPA : Offshore Service Vessel Dynamic Positioning Authority
Ph. D. : Doctor of Philosophy

PMS	**:** Power Management System
PPE	**:** Personal Protective Equipment
PRS	**:** Position Reference System
PSU	**:** Power Supply Unit
PSV	**:** Platform Supply Vessel
RINA	**:** Registro Italiano Navale
RMS	**:** Riser Management System
ROV	**:** Remotely Operated Underwater Vehicle
RS	**:** Russian Maritime Register of Shipping
RTP	**:** Regional Training Provider
SOLAS	**:** Safety of Life at Sea
SPAR	**:** Single Point Anchor Reservoir
SSBL	**:** Super Short Base Line
STCW	**:** Standards of Training Certification and Watchkeeping
TAM	**:** Task Appropriate Mode
TL	**:** Turk Loydu
TLP	**:** Tension Leg Platform
UPS	**:** Uninterrupted Power Supply
VRS	**:** Vertical Reference Sensor
VRU	**:** Vertical Reference Unit
WCF	**:** Worst Case Failure
W2W	**:** Walk to Work Vessel
WSOG	**:** Well Specific Operating Guidelines

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ASSOCIATION RULE MINING FOR IDENTIFYING FACTORS IN DYNAMIC POSITIONING INCIDENTS AND ACCIDENTS

SUMMARY

Dynamic Positioning (DP) systems play a pivotal role in the offshore industry, automating vessel position and heading control. This study investigates thoroughly into the causes of DP incidents using association rule mining, specifically the Apriori algorithm within the Weka program, developed by the University of Waikato. The dataset, drawn from the International Maritime Contractors' Association (IMCA) database spanning 2004 to 2021, encompasses 691 DP incidents, providing a robust foundation for analysis.

Dynamic Positioning is hailed as a technological boon in the offshore industry, ensuring vessels maintain specific positions and headings automatically. Despite its advantages, the need for vigilant monitoring persists, managed by Dynamic Positioning Operators (DPOs). This study aims to reveal the causes of DP incidents through association rule mining, offering a comprehension into the factors contributing to these incidents.

The DP control system relies on data from gyro compasses and position reference systems (PRS) to maintain a vessel's heading and position. During DP operations, the setpoints for the ship's heading and position are defined by the DPO and then processed by the dynamic positioning control system, which provides control signals for both the thrusters and main propulsion systems of the vessel. The DP control system consistently aims to distribute the most efficient thrust to each of its propulsion units that are currently operational. The heading or position measurements are compared to the predicted data generated by the mathematical model. Subsequently, the variations are applied to modify the model.

DP incidents, categorized into loss of redundancy and loss of position, pose significant risks, and understanding their causes is imperative for the industry's safety. Loss of position incidents can also be divided into two different types: drift-off and drive-off.

While numerous studies investigate the causes of marine accidents, a noticeable gap exists in understanding the factors contributing specifically to DP incidents. This research aims to address this gap by employing association rule mining to identify patterns and relationships within a dataset comprising 1352 incidents from the IMCA database.

The Apriori algorithm, integrated into the Weka program, was employed for association rule mining. Weka, a machine-learning workbench, provided a user-friendly interface for dataset analysis. The initial dataset was filtered to 691 incidents for in-depth exploration. The dataset's origin from the IMCA, a reputable source in the maritime offshore industry, enhances the study's credibility.

Analysis reveals primary causes of DP incidents, with thrusters and propulsion failures (24%), computer failures (15%), power-related failures (14%), PRS-related failures (13%), and human factor-related failures (9%) dominating. Secondary causes, notably human factors (54.5%) and electrical problems (13.5%), exhibited an upward trend from 2017 to 2021.

In-depth association rule analysis provides insights into the triggers and outcomes of DP incidents. Accidentally pressing buttons (55.2%) and pressing wrong (standby) buttons (13.1%) emerged as significant triggers. Environmental factors, particularly squalls, swells, and waves, were strongly associated with drift-off incidents (100%). Specific causes, such as power-related failures, thruster or propulsion failures, and PRS-related failures, exhibited distinct outcomes, contributing to a nuanced understanding of DP incidents.

Based on findings, recommendations focus on enhancing DPO training and industry practices. Suggestions include extending the duration of DP simulator courses, revising sea time requirements, and introducing specialized certifications for each vessel types. Simulator-based training should encompass specific actions during emergencies, blackout recovery, and responses to environmental changes.

Extending DP Simulator Courses: Recognizing the significance of practical knowledge, it is recommended to increase the duration of DP simulator courses. This extended training period allows trainee DPOs to gain hands-on experience in a simulated environment, comparing real-life and simulator incidents.

Revising Seatime Requirements: Current sea time requirements post DP simulator course completion may be insufficient for gaining the necessary practical experience. Policymakers are encouraged to consider extending the DP sea time duration (currently set at 2 hours for each DP sea time day) or extending the mandated overall sea time, currently set at 60 days, providing prospective DPOs with more hands-on opportunities. Moreover, it is not recommended to transfer any surplus active sea time days acquired prior to the DP simulator course (Phase 3) to subsequent phase (Phase 4).

Specialized Certification: A specialized certification program is proposed, wherein DPOs gain certification based on their experience with specific vessel types. This approach ensures that DPOs possess vessel-specific knowledge before assuming responsibilities, enhancing overall competency. Industry stakeholders are encouraged to develop expert specialization programs, allowing DPOs with extensive experience on specific types of vessels to obtain specialized certificates, ensuring they possess the requisite knowledge for their roles.

Simulator-Based Emergency Training: DPOs are recommended to undergo simulator-based emergency training covering various scenarios, such as blackout recovery, response to environmental changes, and actions during emergencies. This ensures DPOs are well-prepared for critical situations.

Meteorology Training: Given the association of environmental factors with drift-off incidents, meteorology training combined with DP operations is recommended. This training should include actions during not only emergencies, but also extreme weather conditions such as squalls, solitons, unpredictable changes in current, etc. Additionally, maintaining continuous and vigilant watchkeeping is of significant importance for ensuring the safety of operations.

Power-related Training: Considering the significant impact of power-related failures, blackout recovery training is highlighted as crucial. DPOs, EROs, ETOs, should be well-versed in blackout recovery processes and vessel-specific characteristics. Additionally, it is recommended to provide comprehensive training for DP key personnel before they embark on their vessel assignment. This training should encompass ship-specific thruster/propulsion training, as well as power management training, covering the concept of different propulsion systems, their limitations, and blackout prevention and recovery processes.

Home Training Modules: DP vessel managers and operators should implement home training modules for personnel engaged in DP operations. These modules, covering significant documents related to the vessel and its operations, enhance familiarity and competence. These documents encompass a variety of materials, including, but not limited to, the most recent FMEA and DP annual trial reports of the joining vessel, the DP operation manual, DP incident or failure reports (if any), the latest DP audit report, WSOG, TAM, CAMO, etc.

Human Factor Analysis: A more detailed analysis of human factors and situational awareness is recommended for future research. Understanding the intricacies of human error and awareness can contribute to minimizing risks associated with DP incidents.

Competency Factor Analysis: For future studies, competency factors of DPO for different types of DP vessels can also be identified in more detail. By means of the work, the competency factors can be achieved by taking a specific vessel type or incident model and employing advanced approaches such as machine learning or Bayesian network analysis, among others.

Situational Awareness: Further studies should also explore human factors and situational awareness in greater detail. Situational awareness is vital for DPOs during emergencies, and detailed analysis can contribute to better decision-making and risk mitigation.

This condensed summary provides a detailed overview of the original thesis, retaining the essence of the research while presenting key findings and recommendations. Understanding the causes of DP incidents is crucial for enhancing safety in the offshore industry. The comprehensive recommendations aim to guide industry stakeholders, DP vessel managers and operators, training centers, and policymakers in implementing effective measures to reduce the occurrence of DP incidents and improve overall safety standards.

The implications of this research extend beyond the academic realm, addressing the substantial financial stakes in the offshore industry. By identifying causes and providing targeted recommendations, this study offers a practical guide for industry practitioners. Potential directions for future research include detailed competency factors, advanced analytical approaches, and in-depth analyses of human factors and situational awareness.

In conclusion, this study illuminates the complexities of DP incidents, providing a comprehensive understanding of causes and recommending measures to enhance safety. Given the substantial financial implications of incidents in the offshore industry, this research contributes to a proactive approach, allowing stakeholders to anticipate and address risks effectively.

DİNAMİK KONUMLANDIRMA KAZALARINA AİT FAKTÖRLERİN BİRLİKTELİK KURAL MADENCİLİĞİ İLE TANIMLANMASI

ÖZET

Dinamik konumlandırma, geminin pozisyonunun ve pruva değerinin aktif itme kuvveti aracılığıyla otomatik olarak kontrol edilebildiği bir sistemdir. Sistem, önceden belirlenmiş limitlere ayarlandıktan sonra, gemiyi istenen bir pozisyonda ve pruvada, örneğin bir açık deniz platformuna veya başka bir yapıya mümkün olduğunca yakın tutabilir; hatta gemiyi istenen bir rota üzerinde hareket ettirebilir.

Dinamik konumlandırma sistemleri, açık deniz endüstrisi için önemli bir teknolojik gelişme sağlamaktadır. DP sistemi sürekli olarak, DPO (Dinamik Konumlandırma Operatörü) olarak adlandırılan yetkili bir operatör tarafından izlenmeli ve gerekli ayarlar yapılmalıdır.

DP sistemi, geminin pozisyonunu istenilen koordinatta tutabilmek için en az bir pozisyon referans sistemi ile birlikte pruva değerini korumak üzere cayro pusulalardan veri alır. İstenilen pruva değerinden veya pozisyondan bir sapma olduğunda, oluşan farklılık sistem tarafından otomatik ve sürekli olarak tespit edilir. Gemiyi istenilen pruvaya veya pozisyonaa geri getirmek için gerekli ayarlamalar DP sistemi tarafından otomatik olarak yapılır.

Geminin pruvası ve pozisyonu için gerekli ayarlar, DPO tarafından belirlenir ve daha sonra DP kontrol sistemi tarafından işlenerek geminin itici ve ana tahrik sistemlerine kontrol sinyalleri sağlanır. DP kontrol sistemi her zaman aktif olan her bir tahrik ünitesine optimum itme gücünü tahsis etmeyi amaçlar. Pruva ve pozisyon hesaplamaları, matematiksel model tarafından üretilen tahmini verilerle karşılaştırılır. Saptanan farklılıklar daha sonra modelin güncellenmesi için kullanılır.

DP kazaları genellikle iki kategoriye ayrılır; LoR (yedekleme kaybı) ve LoP (pozisyon kaybı). Pozisyon kaybı kazaları da iki farklı türe ayrılabilir; drift-off (sürüklenme) ve drive-off (uzaklaşma). Deniz kazalarının nedenlerini inceleyen birçok araştırma, çeşitli araştırmacılar tarafından yapılmıştır. Ancak, dinamik konumlandırma kazalarının sebeplerine ilişkin literatürde çok fazla çalışma bulunmadığı tespit edilmiştir.

Bu doktora tezi, birliktelik kural madenciliği ve Apriori algoritmasını kullanarak DP kazalarının potansiyel nedenlerine yönelik kapsamlı bir araştırma yapmayı amaçlamaktadır. Aynı zamanda, dinamik konumlandırma kazalarındaki güçlü birliktelik kurallarının belirlenmesi ve DP kazalarının oluşumunu etkileyen faktörlerin analiz edilmesi hedeflenmektedir.

Birliktelik analizi, büyük veri kümesinde gizlenmiş önemli ilişkileri bulma konusunda etkilidir. Veri kümelerini analiz etmek ve güçlü birliktelik kurallarının tanımlanması için Weka programı kullanılmıştır. Yeni Zelanda'daki Waikato Üniversitesi tarafından geliştirilen Weka programı, bir makine öğrenme çalışma tezgahıdır ve kullanıcı dostu bir arayüz ile veritabanı analizi imkanı sunmaktadır (Garner, 1995).

Weka programı, kullanımı kolay bir açık kaynaklı makine öğrenimi yazılım programı olup, grafik kullanıcı arayüzü, standart terminal uygulamaları veya Java API (Uygulama Programlama Arayüzü) aracılığıyla erişilebilmektedir. (Frank vd., 2005).

Bu araştırmanın sonuçları, DP kazalarına sebep olan en yaygın ana ve ikincil nedenleri ortaya çıkarılmıştır. Doktora tezi sonuçları, DPO'ların faktörler arasındaki potansiyel etkileşimi anlamalarını ve gelecekteki olası DP kazalarını azaltmak için çözümler ve öneriler sunmalarını sağlayacaktır.

Çalışmada kullanılan ilk ham veriler, 2004 ve 2021 yılları arasında gerçekleşen toplam 1352 dinamik konumlandırma (DP) kazaları ile istenmeyen DP olaylarını içermekte olup, IMCA (Uluslararası Denizcilik Müteahhitleri Birliği) veri tabanından temin edilmiştir. Filtreleme sürecinden geçirildikten sonra, toplam 691 DP kazası, DP kazalarına neden olan potansiyel faktörleri ve bu faktörler arasındaki ilişkileri belirlemek amacıyla analiz için kullanılmıştır.

Genel olarak, sonuçlar DP kazaları için önemli ana nedenlerin sırasıyla thruster/pervane sistemleri (24%), bilgisayar kaynaklı (15%), güç kaynaklı (14%), PRS (pozisyon referans sistemi) kaynaklı (13%) ve insan faktörüne bağlı arızalar (%9) olduğunu ortaya koymaktadır.

İkinci olarak, 2017'den 2021'e kadar olan beş yıllık dönemde, insan faktöründen (54.5%), elektrik sorunlarından (13.5%) oranında kaynaklanan ikincil nedenlerde önemli bir artış olmuştur.

Sonuçlara göre, insan faktörünün DP kazalarının oluşumunda önemli bir rol oynadığı ortaya çıkmakta olup, bulgular ışığında aşağıdaki sonuçlar ve öneriler sunulmaktadır.

Yapılan analizlere göre, bir düğmeye yanlışlıkla basmanın DP kazalarında 55.2%'lik bir oranla en yaygın tetikleyici unsure olduğu saptanmıştır. Yanlış veya stand-by (bekleme) düğmesine basmanın oranı ise 13.1% olarak belirlenmiştir. Diğer tetikleyici diğer faktörler arasında personelin bilgi eksikliği 15% ve yanlış komut verme ise 6.6% oranında bulunmaktadır.

Güçlü birliktelik kuralları açısından, pozisyon kaybı (LoP) ile sonuçlanan kazalar incelendiğinde, fırtına, ölü dalga ve dalgalar, ani akıntı değişimi gibi çevresel faktörlere sahip öncüllerin her zaman (drift-off) sürüklenme ile sonuçlandığı belirlenmiştir.

İkinci olarak, eğer ana neden güçle ilgili arızalar ise, sonuç 100% oranında (drift-off) sürüklenme ile sonuçlanmakta; ancak ana neden veya ikincil neden insan faktörü ile ilgili ise, sonuç 75% oranında (drift-off) sürüklenme kazası ile neticelenmektedir. Bu kazalar arasında, stand-by düğmesine basılmasının, 100% oranında (drift-off) sürüklenmeye sebep olduğu tespit edilmiştir. Kötü prosedürlere sahip ikincil nedenlerin de 67% oranında (drift-off) sürüklenme kazalarına yol açtığı belirlenmiştir.

Eğer ana neden thruster/pervane sistemleri kaynaklı ise, sonuç 65% oranında (drift-off) sürüklenme kazası ile sonuçlanmaktadır. Öte yandan, öncül neden pozisyon referans sistemi (PRS) ile ilgili arızalardan kaynaklanıyorsa, sonuç 85% oranında (drive-off) uzaklaşma kazaları ile sonuçlanmaktadır.

Sonuçlar ayrıca (drive-off) uzaklaşma kazalarının çoğunun Destek Gemisi (PSV) operasyonları sırasında, (drift-off) sürüklenme kazalarının çoğunun ise sondaj operasyonları sırasında meydana geldiğini göstermektedir.

Bulgu-1: 'DP personelinin bilgi eksikliği' DP kazalarını tetiklemede 15%'lik bir orana sahiptir. Ayrıca, 'yanlış komut verilmesi' 6.6%'lık bir orana sahiptir. Bu durumun kişisel deneyim ve bilgi eksikliği ile ilgili olduğu düşünülmektedir.

Öneri-1: Daha fazla pratik deneyim edinmek için DP simülatör kurs süresinin artırılması önerilmektedir. Aday DPO'lar, DP simülatöründe ne kadar çok zaman geçirirlerse o kadar çok pratik deneyime sahip olacaklardır. Simülatör ortamında acil durum ve kazaları canlandırarak, DPO'ların deneyim kazanmalarını sağlamanın, gerçek kazalara kıyasla maliyet açısından daha uygun olduğu ön görülmektedir.

Bulgu-2: Uygulama sırasında kazanılan deneyimin daha etkili olduğu değerlendirilmektedir. NI'nin mevcut gerekliliklerine göre; DP simülatör kursundan (Seviye-3) sonra mecburi deniz hizmet süresi 60 aktif DP günüdür. Aday DPO'lar için DP Temel Giriş kursundan (Seviye-1) sonra, DP Simülatör kursundan (Seviye-3) önce gerçekleştirilen maksimum 30 aktif DP gününü ileri staj aşamasına (Seviye-4) transfer etme seçeneği vardır.

Öneri-2a: Bir DP deniz hizmet günü, günde sadece iki saat içerdiğinden, DP simülatör kursunu (Seviye-3) tamamladıktan sonra gerekli olan (60) gün aktif DP deniz hizmet süresinin yetersiz olduğu düşünülmektedir. Sonuç olarak, politika yapıcılara yönelik bir diğer öneri; DP deniz hizmet gününün 2 saat olan süresinin artırılması ya da Seviye-4 süresince toplanması gerekli (60) gün olan aktif DP deniz hizmet süresinin yükseltilmesidir. Bu değişiklik sayesinde aday DPO'lar pratik deneyim kazanmak için daha fazla şansa sahip olacaklardır. (İlişkili referans kurallar: 1.7, 1.8, 2.1, 2.2, 2.7, 2.11, 3.1, 3.2, 3.3, 3.4, 4.2, 4.9, 4.10 ve 4.17)

Öneri-2b: Seviye-4 süresince talep edilen mecburi aktif DP günlerinin sadece DP Simülatörü eğitimi (Seviye-3) tamamlandıktan sonra icra edilmesi önemle tavsiye edilmektedir. DP Simülatörü kursundan (Seviye-3) önce kazanılan fazladan aktif deniz süresi günleri Seviye-4 gibi daha ileri aşamalara aktarılmamalıdır. (İlişkili referans kurallar: 1.7, 1.8, 2.1, 2.2, 2.7, 2.11, 3.1, 3.2, 3.3, 3.4, 4.2, 4.9, 4.10 ve 4.17)

Bulgu-3: Güçlü ilişkilendirme kurallarına göre, çevresel faktörler her zaman LoP (pozisyon kaybı) drift-off (sürüklenme) kazasıyla sonuçlanmaktadır.

Öneri-3: Kötü hava koşullarında (fırtına, soliton, akıntı gibi) DP sistemiyle alakalı yapılması gerekenler göz önünde tutularak, DP operasyonları ile birleştirilmiş meteoroloji eğitiminin tüm DPO'lara verilmesi tavsiye edilmektedir. Ayrıca, DP vardiyası tutarken sürekli gözcülük yapılması ve hava koşullarının izlenmesi önemlidir. (İlişkili referans kurallar: 1.5, 2.1, 3.3, 3.4, 3.5, 3.6, 4.1 ve 4.5)

Bulgu-4: Sonuçlar, Tablo 5.1'de görüldüğü üzere, DP olaylarının başlıca nedenlerinin thruster ve pervanelerle ilgili arızalar (24%), bilgisayarla ilgili arızalar (15%), güçle ilgili arızalar (14%), PRS arızaları (13%) ve insan faktörüyle ilgili arızalar (9%) olduğunu ortaya koymaktadır.

Öneri-4a: Güç kesintisi (black-out) geri kurtarma eğitimi, DP sisteminde görev alan mürettebat için büyük önem taşımaktadır. Tüm DP operatörleri ve ERO'lar gemilerinin spesifik özelliklerini, güç kesintisi (black-out) geri kurtarma sürecini ve süresini bilmekten sorumludur. (İlişkili referans kurallar: 5.3)

Öneri-4b: Ek olarak, DP personeline (DPO'lar, Gemi Makine Mühendisleri, ETO'lar) gemilerine katılmadan önce bazı eğitimlerin verilmesi tavsiye edilir; geminin pervane/tahrik sistemi eğitimi, güç yönetimi eğitimi (Farklı tahrik sistemleri kavram ve sınırlamaları, güç kesintisi (black-out) önleme ve geri kurtarma süreci, vb. (İlişkili referans kurallar: 5.3)

Bulgu-5: Bu tez çalışmasının sonuçlarına göre, yanlışlıkla bir düğmeye basmanın 55,2%'lik oranla DP kazalarını tetikleyen önemli bir neden olduğu saptanmıştır.

Öneri-5: Gelecekteki araştırmalar için farkındalığı artırmak ve DP kazalarına yönelik riskleri en aza indirmek amacıyla insan faktörü ve durumsal farkındalığa ilişkin daha detaylı bir analiz yapılması önerilmektedir. Bu çalışmanın kısıtlamaları, araştırmacıların DP kazalarındaki hatalara katkıda bulunabilecek insan faktörünün durumsal farkındalığının ayrıntılı bir analizini yapmasına izin vermemektedir.

Bulgu-6: Bu tez çalışmasının sonuçlarına, DP kazalarının sayısının artmaya devam ettiğini kanıtlamaktadır.

Öneri-6: DPO'ların DP acil durumları sırasında nasıl hareket edeceklerine dair özel bir kurs almaları önemle tavsiye edilmektedir. Bu simülatör tabanlı bir eğitim olup, operatörlerin nasıl tepki vereceğini gösteren DP Acil Durumları olarak adlandırılır;

- Tüm rüzgar sensörlerinin kaybedilmesi durumunda ne yapılmalıdır?
- Tüm cayro pusulaların kaybedilmesi durumunda ne yapılmalıdır?
- Bir veya daha fazla PRS (pozisyon referans sistemi) kaybedildiğinde ne yapılmalıdır?
- Güç kesintisi (black-out) durumunda ne yapılmalıdır?
- Yedekleme kaybı (LoR) olması durumunda ne yapılmalıdır?
- Drift-off sürüklenme (LoP) durumunda ne yapılmalıdır?
- Drive-off uzaklaşma (LoP) durumunda ne yapılmalıdır?
- Deniz akıntısında bir değişiklik veya rüzgar hızında bir değişiklik, bora, fırtına, soliton vb. gibi ani bir çevresel değişiklik olması durumunda yapılması gerekenler nelerdir?

Bulgu-7: DP kazalarına karışan gemi tipi/operasyon türü dalgıç gemileri (17.3%), sondaj gemileri (16.4%), ROV gemileri (14.6%) ve platform destek/kargo gemileri (12.5%) olarak sıralanabilir. Dalgıç ve sondaj gemilerindeki DP ekipman sınıfının çoğunlukla DP-3 donanımlı, diğer tip gemilerdeki DP ekipman sınıfının ise DP-2 veya DP-1 donanımlı olduğu saptanmıştır. Bir destek gemisi ile bir sondaj gemisinde kazanılan DP deneyiminin nitelik olarak, uygulanan DP saatlerinin ise nicelik olarak aynı olmadığı anlaşılmaktadır. DP sistemi ve prensipleri temelde benzer olsa da, farklı tipteki açık deniz gemilerinin ve bu gemilerdeki yapılan operasyonların içeriği birbirinden farklı olabilmektedir.

Öneri-7: Bu kapsamda, sektör için gemi tiplerine göre uzmanlık programı geliştirilmesi önerilmektedir. DPO, çalışacağı gemi tipine uygun uzmanlık sertifikasına sahip olmadığı sürece, özel bilgi ve deneyim kazanana kadar, belli bir süre veya DP saati biriktirene kadar, sınırsız DPO sertifikasına haiz olsa bile herhangi bir sorumluluk almadan, ilave DPO (stajyer DPO) olarak o tip gemide istihdam edilebilir.

Ayrıca, DP gemi işletmecileri/operatörleri, DP operasyonlarında görev alan personeline (DPO'lar, Gemi Makine Mühendisleri ve ETO'lar) gemi tipine uygun tanıma (familiarization) eğitimi sağlamalıdır. Bu eğitim modülü, uzaktan/evden eğitim olarak adlandırılır ve gemiye katılmadan önce verilmelidir. Örneğin, sondaj gemisine tanıma eğitimi, ilgili personelin gemiye katılmadan önce, görev yapacağı gemiye özgü DP sisteminin marka ve modelini, yazılımını, ekipman türlerini ve diğer ilgili kısımlarını öğrenmesi için uygun müfredat programı hazırlanmalıdır. Uzaktan/Evden eğitim modülüne göre, DP operasyonlarından sorumlu ilgili personel, görev yapacağı gemiye ait bazı önemli belgeleri de gözden geçirmelidir. Bu dokümanlar arasında gemiye ait son FMEA, yıllık DP deneme raporları, DP operasyon el kitabı, (varsa) DP kaza/arıza raporları, en son DP denetim raporu, WSOG, TAM, CAMO, vb. yer almaktadır.

DPO'ların eğitiminin güçlendirilmesi, eğitim içeriğinin ve kalitesinin iyileştirilmesi hiç şüphesiz DP operatörlerinin kalitesini artıracak ve insan hatasından kaynaklanan DP kazalarının meydana gelme olasılığını azaltacaktır.

Gelecekte yapılacak çalışmalara atfen, farklı tipteki DP sistemli gemiler için DPO'ların yetkinlik faktörleri daha detaylı bir şekilde belirlenebilir. Çalışma sayesinde, makine öğrenimi veya Bayesian ağ yöntemi gibi yöntemler aracılığıyla belirli bir gemi tipi veya olay modeli alınarak yetkinlik faktörlerine ulaşılabilir.

Ek olarak, durumsal farkındalık bireylerin daha uyanık olmalarını ve acil durumlarda DPO'lar için hayati öneme sahip olan daha iyi karar vermelerini sağlar. Araştırmacıların, farkındalığı artırmak ve DP kazalarına yönelik riskleri en aza indirmek için insan faktörü ve durumsal farkındalık ile ilgili daha detaylı analizler yapmaları gelecekteki çalışmalar için tavsiye edilmektedir.

Açık deniz operasyonlarında yaşanan olası kazaların sonuçları genellikle karşılanamayacak kadar maliyetli ve zararlı olmaktadır. Bu nedenle, eğitim maliyetleri şirketlerin yıllık bütçelerinde büyük bir yüzdeyi kapsamaktadır. Bu çalışmanın sonunda, DP kazalarının nedenleri ile ilgili olarak açık deniz operasyonlarına farklı bir bakış açısı ve etkili bir kaynak desteği sağlanması hedeflenmektedir. Özellikle, DP gemi işletme şirketleri, DP eğitim merkezleri ve DP operatörleri, DP kazalarına sebep olabilecek faktörleri ve bu faktörler arasındaki güçlü ilişkileri daha iyi anlayabilmek için bu çalışmayı bir kılavuz olarak kullanabileceklerdir. Bu araştırma aynı zamanda DPO'ların risklerden önceden şüphelenmelerini ve çok geç olmadan önlem almalarını sağlayacaktır.

Sonuç olarak, bu doktora tez çalışması, dinamik konumlandırma (DP) sistemli gemilerde meydana gelen kazaların nedenleri üzerine kapsamlı bir inceleme sunmaktadır. Ana nedenler arasında thruster/pervane sistem arızaları (24%), bilgisayar arızaları (15%), güç kaynaklı arızalar (14%), pozisyon referans sistemi arızaları (13%), ve insan faktörüne bağlı arızalar (9%) öne çıkmaktadır. Özellikle, 2017'den 2021'e kadar olan dönemde insan faktöründen kaynaklanan ikincil nedenlerde önemli bir artış (54.5%) gözlemlenmiştir. Bu çalışma neticesinde, DP operatörlerinin eğitimine ve yetkinliğine odaklanarak, sektöre özel eğitim programları ve uzmanlık sertifikalarının geliştirilmesi önerilmektedir. Son olarak, gelecekteki çalışmalar için farkındalığı artırmak ve riskleri en aza indirmek adına daha detaylı analizlerin yapılması önemlidir. Bu çalışmaların sonuçları, gelecekteki DP kazalarını azaltmak için sektördeki paydaşlar için değerli bir kılavuz sunmaktadır.

1. INTRODUCTION

The offshore oil and gas business is inextricably linked to and influences the national energy stability and economic security of countries. The vessels engaged in offshore operations are mostly installed with dynamic positioning (DP) systems. These vessels may be involved in loss of position (LoP) mishaps during DP operations. Because of the sensitivity of DP vessel operations, the ramifications of such occurrences have major consequences. Hence, it is crucial to conduct DP incident analysis and explore the potential causal connections among the components in order to effectively prevent DP incidents.

Since very early times, marine accidents have always been important for the industry. Because of that, the lessons learned usually lead to the need for a new requirement, rule, or regulation to be adopted. Particularly, DP incidents are thought to have even more critical consequences due to the nature of offshore operations. Any serious failure of the DP system may cause vessels to drift-off or drive-off which can create a loss of position. These undesirable conditions may also result in consequences such as a contact platform, collision with another vessel or fixed structure, damaging a drill string or pipe, endangering oil and gas wells, polluting the marine environment, etc.

As per the definition provided by the International Maritime Organisation (IMO), a dynamic positioning (DP) vessel is described as ‘‘a unit or a vessel that automatically maintains its position (fixed location or predetermined track) exclusively by means of thruster force’’ (IMO, 1994; IMO, 2017; IMCA, 2022). Additionally, IMO describes a DP system as “the complete installation necessary for dynamically positioning a vessel comprising the following sub-systems: power system, thruster system, and DP control system” (IMO, 1994; IMO, 2017).

Dynamic positioning is a system that enables a vessel to control her position and heading automatically through the utilisation of active thrust, according to the IMCA

(International Maritime Contractors' Association). To maintain the vessel in a predetermined position automatically, the vessel uses its own thrusters, propulsion system, and rudder units. By means of a dynamic positioning system, vessels can keep their positions in the required position as reliable as possible and as close to other offshore structures, platforms, vessels, or the desired position. Due to the sensitivity of operation such as drilling, diving, or anchor handling operations, the system is required to be continuously monitored by a competent dynamic positioning operator called DPO or DP operator.

To maintain the ship's heading, the DP control system receives data from gyro compasses and a minimum of one position reference system (PRS) and enables the DP control system to maintain the vessel's position at a desired point. When there is a deviation from the predetermined heading or position, the differences are automatically and continuously detected by the system, which also makes the necessary adjustments to realign the vessel back to its predetermined heading or position. During DP operations, the setpoints for the ship's heading and position are described by the DPO. Afterwards, they are processed by the control system of DP, which utilises signals to the vessel's thrusters and main propulsion systems. The DP control system consistently aims to allocate the most optimum thrust to each of its propulsion units that are currently operational. The heading or position of the vessel is compared to the predicted data generated by the mathematical model. Subsequently, the variations are applied to update the model.

1.1 Six Degrees of Freedom

Any vessel in water is subject to external forces such as wind, waves, and currents. Also, the vessel's own propulsion system generates forces that create movement. Consequently, there are six different movements for each floating unit (vessel), which is called ''six degrees of freedom''. These movements are illustrated in Figure 1.1 and can be listed as pitch, roll, heave and yaw, surge, and sway. While heave, pitch, and roll can't be controlled by a vessel or a DP operator, yaw, surge and sway movements can be controlled by a DPO using the DP system.

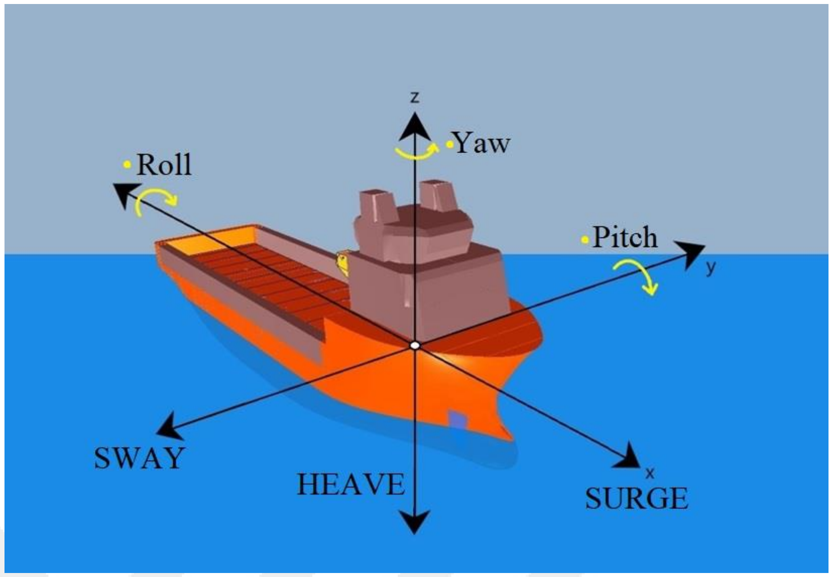

Figure 1.1 : Six degrees of freedom.

Surge is the movement of a vessel in the fore and aft directions. Sway is the lateral movement of a vessel (to port or starboard direction). Yaw is the control of a vessel's heading (port or starboard). The three motions, which can be controlled by the vessel's dynamic positioning system, are illustrated in Figure 1.2.

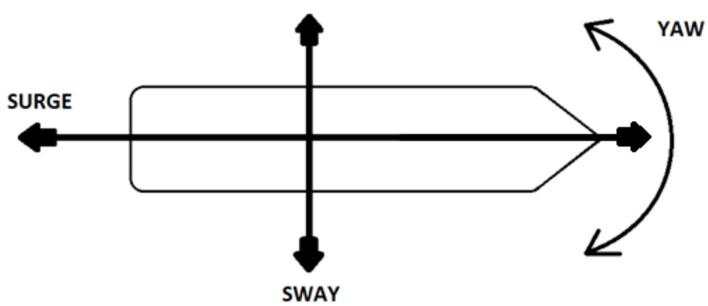

Figure 1.2 : Controllable movements of a vessel.

On the contrary, Figure 1.3 reveals the movements that cannot be controlled by DPO but can be measured by some equipment. These uncontrollable motions are called heave, pitch, and roll. Heave is the up-and-down movement of a ship. Besides, roll is the inclination of a vessel from port to starboard or vice versa, while pitch is the inclination from bow to stern or vice versa. The motions of pitch and roll cannot be controlled; however, their values can be measured by using vertical reference sensors in the DP system, same as heave motion, that can be measured by the vessel's draft.

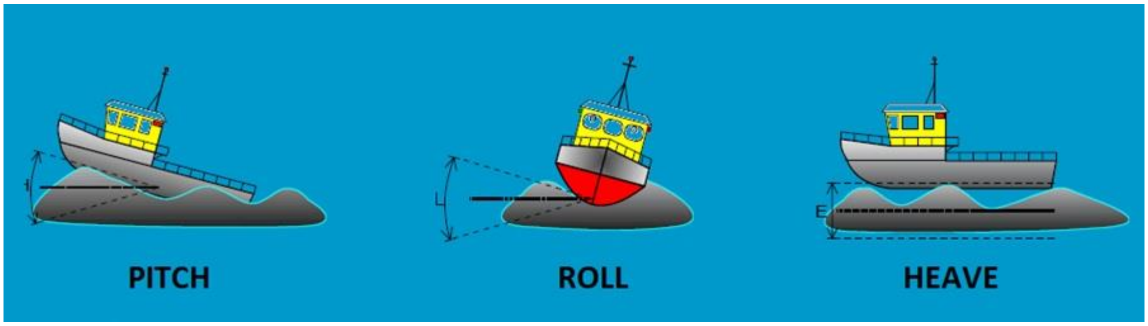

Figure 1.3 : Uncontrolled movements of a vessel (Kongsberg, 2021).

1.2 Main Components and System Structure of DP System

The dynamic positioning (DP) system has six sub-systems. Figure 1.4 illustrates the primary components of a dynamic positioning system.

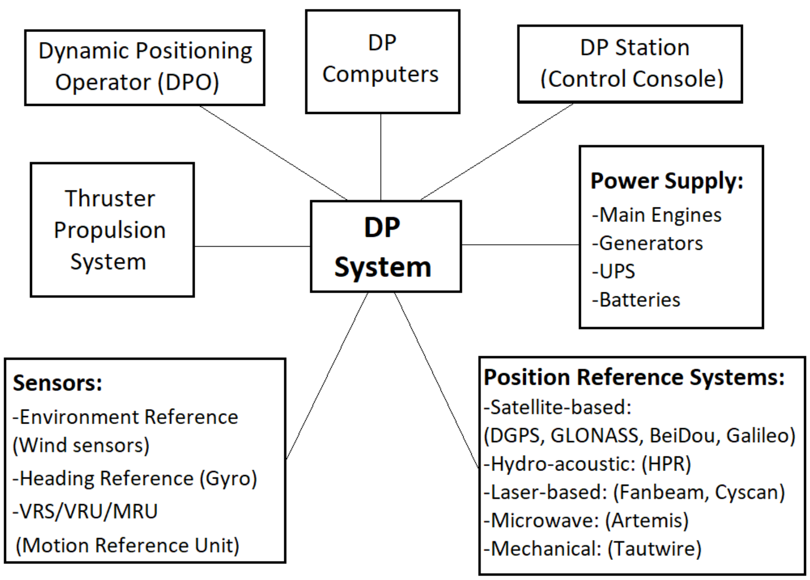

Figure 1.4 : Main components of DP system.

To perform DP operations, the six components should be working effectively according to the requirements. A certified and well-trained DPO, DP station, DP computers, thrusters and propulsion system, power supply, and required sensors such as position reference systems, wind sensor(s), gyro(s), and MRU (Motion Reference Units) are required. Figure 1.5 is a simplified block diagram illustrating the components of a dynamic positioning system.

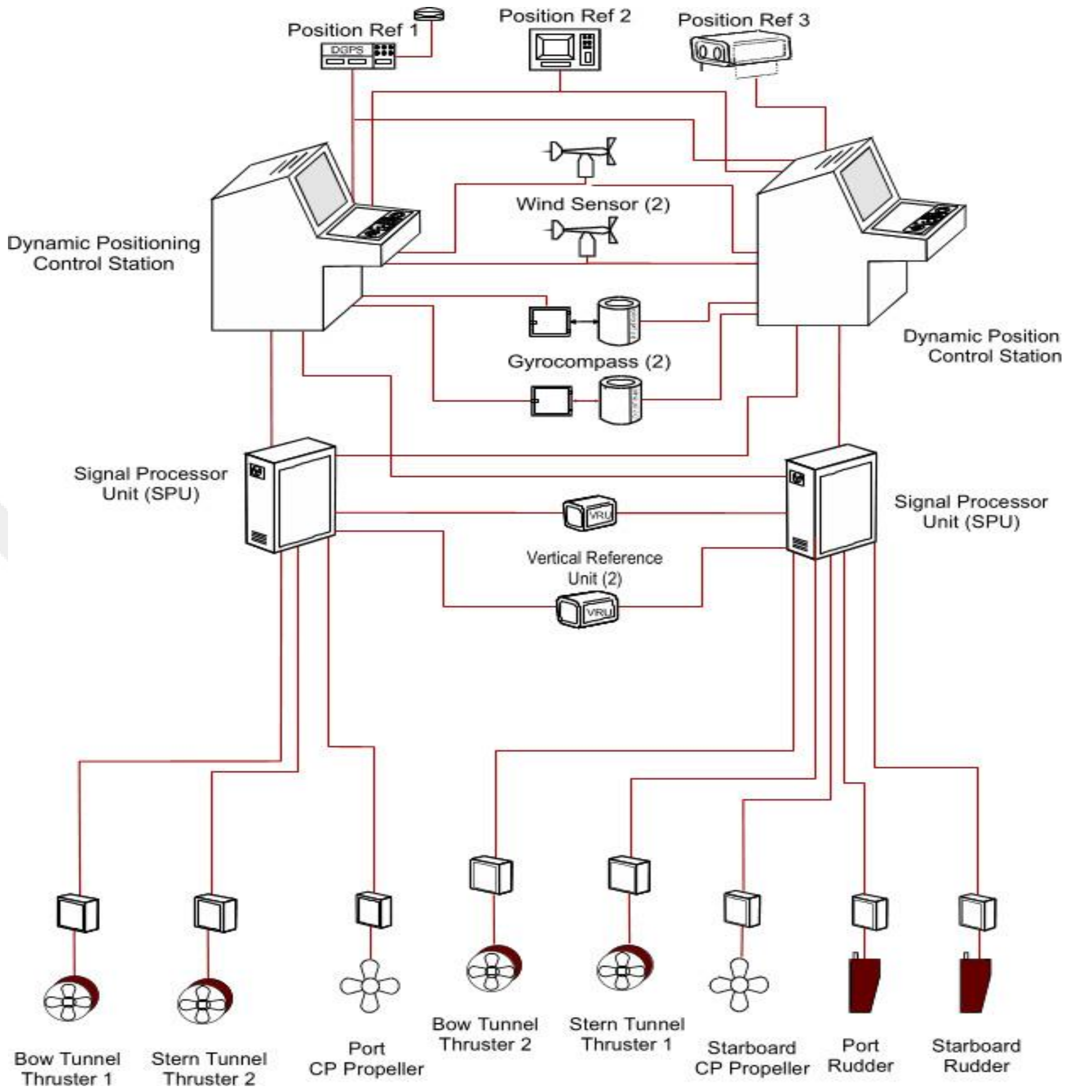

Figure 1.5 : An example of a simplified block diagram of DP system (Nedcon, 2021).

1.2.1 Sensors

1.2.1.1 Position reference systems

There are different position reference systems in the world. The selection of PRS depends on the vessel's requirements, working conditions, and her role in the project. PRS can be either an absolute system that can give the vessel's geographic position or a relative system that can provide the vessel's position relative to another reference.

The most known position reference systems are as follows:

DGNSS: DGPS (the US), GLONASS (Russia), Galileo (EU), and BeiDou (China) are some of the most popular global navigation satellite systems used onboard DP vessels.

The satellite system provides the geographical position of the vessel. Utilising a differential GPS, the accuracy is much higher than that of normal GPS. Accuracy is less than 1 m, which is also accepted for DP operations. GLONASS accuracy is better than DGPS in higher latitudes.

Laser-based system: The system principle is a laser-based location tracking system using optical radar. Auto-tracking of one or more targets is usually managed by using a designated reflector. The equipment locks on a single or multiple targets on the offshore structure, commonly known as a reflector. Pulses are transmitted and received in order to determine both the range and bearing. There are two laser-based systems on the market, which are called Fanbeam and CyScan.

Radio-based position reference systems: Range and bearing are found through radio waves. In the offshore industry, the most common equipment is Radius, RadaScan, and Artemis. The basis of a position by Artemis is that of obtaining the range and bearing of a mobile station from some known fixed objects. (Chas & Ferreiro, 2008)

Taut wire: This system is based on a mechanical system. The process involves the utilisation of a mechanical wire to lower a depressor weight to the seabed. The wire is handled by a constant-tension winch located on the vessel's deck. Used usually on short-range (shallow waters) and when the DP vessel is expected to keep her position in the long term. The angle of the wire is measured using angle sensors located at the final point of the crane's jib. The length and angle of the wire define the vessel's position on the sensor, which will detect the movement of the vessel.

Hydro-acoustic (HPR): The principle is based on communication at hydro-acoustic frequencies, achieved by the interaction between a transducer or several transducers fixed on the hull of a vessel and one or more transponders positioned on the seabed. The system may use SSBL (Super Short Base Line) or LBL (Long Base Line) methods. Although the system is not as accurate as DGNSS, it is considered a reliable position reference system. It should also be noted that noise created by thrusters can affect the system's accuracy.

1.2.1.2 Environment reference system (wind sensors)

Wind sensors: Wind is usually one of the strongest external effects on the vessel, causing a change of position or heading. Wind speed and direction are measured by anemometers, which are called wind sensors. The measured data is sent to the DP control system. Also, the mathematical model will use data received from wind sensors to predict the vessel's movements and future counteractions. DP systems will then calculate the thruster demand in terms of force and direction.

Motion Reference Units: Vertical reference sensors or units (VRS, VRU, or MRU) measure and display roll and pitch motions. MRU is usually located on the bottom part of a ship and measures the differences between the vertical orientation specific to a given location and the standard plane of reference for the vessel to find pitch and roll. As mentioned previously, pitch, roll, and heave cannot be controlled by the DP system. However, measurement of pitch and roll is important for the system to provide accurate compensation for reference system readings, which are corrected for pitch and roll using MRU.

Doppler Log: Doppler Log is a speed measurer. It measures a vessel's speed over the seabed using sounds.

1.2.1.3 Heading reference system (Gyro)

The heading is measured by gyro compasses and delivered to the DP system. The minimum number of gyro compasses required to be installed onboard depends on the DP class of the vessel.

1.2.2 Thruster and propulsion system

The propulsion system of DP vessels is an essential system for DP vessels. The most common propulsion types are as follows:

Conventional system (propellers with rudders): This is a conventional system that includes rudders. Propellers can be either fixed pitch (FPP) or controllable pitch (CPP). There can be one or more propellers and rudders. The vessel can thrust fore-and-aft, and athwart the ships using this system. With the help of rudders and propellers, the vessel is tried to move in a sway direction, although side thrust is not efficient under these circumstances. Therefore, the industry usually provides additional side tunnel thrusters to ensure efficient DP station-keeping operations.

Tunnel thrusters are mounted inside the vessel bottom, usually in forward and aft locations, but rarely also amidships. These thrusters enable a vessel to move sideways to port or starboard effectively. It should be kept in mind that tunnel thrusters are not effective at high speeds or when the draft of the vessel is low and the thrusters are close to the water line.

Azimuth thrusters have flexibility in direction, and they can provide thrust in any way by rotating these thrusters at 360 degrees. Propellers can be fixed (variable speed) or pitch-controlled. Azimuth thrusters can also be retractable in horizontal and vertical directions due to their vulnerability based on grounding in shallow water.

Another system is Azipod, which is also able to turn 360 degrees and provides high manoeuvrability. While the propeller in the Azimuth propulsion system is driven by a diesel engine or electrical motor within the vessel's hull, the Azipod system's propeller is directly connected to a motor shaft, where the electrical motor is housed within the propulsion unit, outside of the vessel's hull.

1.2.3 Power supply system

The power system has vital importance on a DP ship. Power needs to be produced by engines or generators and supplied for thrusters, other manoeuvring systems installed onboard, DP control units, reference systems, and sensors. Most offshore vessels consume marine diesel or gas oil (MDO or MGO).

Depending on the type of ship and manufacturer, class of DP system, and environmental condition, there are several modes that can be shifted from one to another. Some of them called DP nice weather, DP hard weather, DP manoeuvre mode, DP sea mode, etc. Different configurations can be settled depending on the conditions of several factors.

The power supply system provides different levels of power for each mode. At sea, where there is no high risk, the system can be supplied from a connected bus tie. However, during DP operations, the system is advised to be separately supplied by different bus ties for redundancy. These controls can be made using a power management system (PMS), which is created to control and monitor the propulsion system (main engines, generators, switchboards, consumption, etc.).

Switchboards provide electrical distribution from thrusters to other consumers at different voltage levels (6.6 kV, 440 V, and 220 V). By means of bus tie breaker(s), the switchboards can be connected or separated. A typical example of a power distribution diagram for an OSV is illustrated in Figure 1.6.

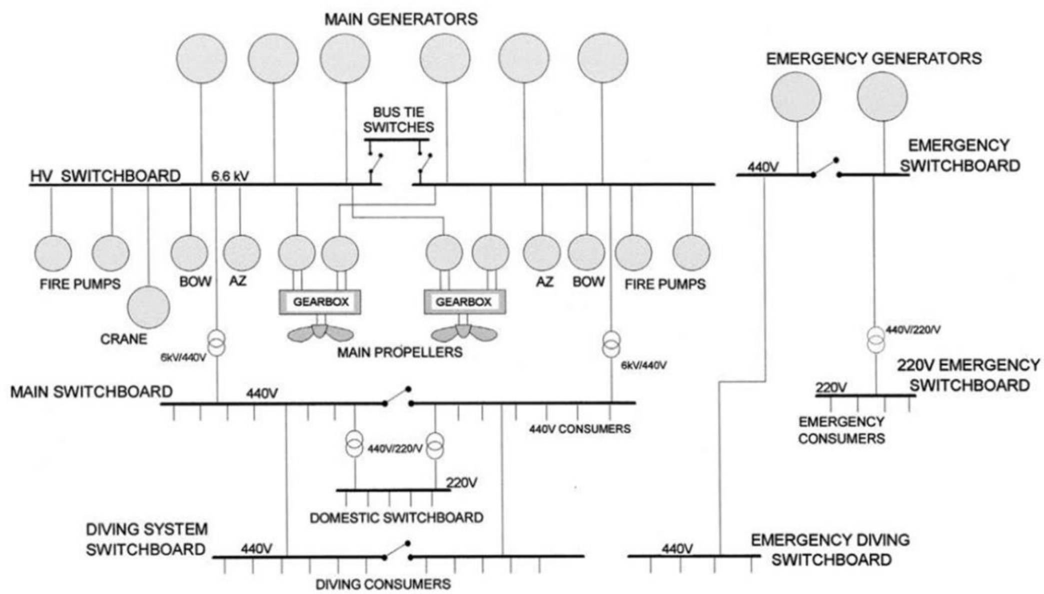

Figure 1.6 : A typical power distribution system for OSV (Bray, D., 2003).

There is also an UPS (Uninterrupted Power Supply) system for DP vessels. This will supply DP computers, the DP control system, reference systems, and sensors in the event of a failure in the main power system of a DP vessel. The device has the capacity to provide a minimum of 30 minutes of electricity. Due to the redundancy requirements, for DP-2 and DP-3 vessels, different DP control units, or PRS, should be connected to different UPS.

1.2.4 DP station (Console)

It is also called a DP operator station. The DP console consists of some monitors where the DPO can monitor the vessel's movements and DP settings. Also, there are panels that have buttons, switches, alarms, and joysticks to make necessary settings, changes, or commands.

1.2.5 DP computer (Processor)

The processor that operates DP software is called a DP computer. The DP computer is assigned only for DP operation purposes. Depending on the DP equipment class, there might be one, two, or three DP computers installed onboard. Processors may work via the intranet or local area network (LAN).

1.2.6 DPO (Dynamic Positioning Operator)

DPO is the operator who is responsible for controlling the vessel's movement by setting, using, and monitoring the DP system as required. The Nautical Institute is the most common organisation that manages the training and certification system on behalf of IMCA. However, there are other training schemes, such as those by Det Norske Veritas (DNV) and the Offshore Service Vessel Dynamic Positioning Authority (OSVDPA). Any deck cadet or watchkeeping officer who would like to become a DPO must follow the training steps to achieve a DPO certificate.

1.3 Single Failure, Redundancy, and Loss of Position

To enhance one's comprehension of the distinctions between DP classes, it is important to first clarify the definitions of single failure and redundancy. A single failure can be described as any active part, system, or component. To give an example, it includes main engines, thrusters, propellers, generators, switchboards, remotely operated valves, etc. Additionally, it also includes any normally static components such as cables, pipes, manual valves, etc. A single fault is known to have the maximum detrimental effect on the DP capacity, as assessed by the FMEA process.

In accordance with the IMO, redundancy is the ability of a system or component to retain or regain its function when a single failure occurs. Using various components or systems performing the same functions, redundancy can be accomplished. Loss of redundancy is described as losing the ability of a system or component and not being able to regain its function when there is a single failure. In other words, it can be explained as losing its backup system, which will enable the DP system to still keep its position until prevention action is taken. Utilising redundancy, the DP vessel will not lose her position immediately and therefore will not cause any prompt accidents. In case of an emergency, it allows DPOs to terminate the operation and safely move away until the problem has been identified and corrected. Worst-case failure refers to a specific defect (a single fault) that has been detected within the DP system.

On the other hand, loss of position can be described as a major or minor loss of position causing the vessel to move from the desired position uncontrolled. Loss of position can happen in two different ways: drift-off or drive-off. Drift-off incidents can be explained as the inability to counteract forces to keep the vessel in a desired position after a loss of thrusters or propulsion power. In other words, thrusters' commands from the DP control unit either freeze or go to zero, in which situation the vessel drifts off from the desired position. On the other hand, a drive-off incident is a situation in which the thrusters' commands go to full thrust level due to an error such as mechanical, electrical, or degradation of PRS movement in the wrong reference direction. Consequently, this problem may cause the DP vessel to drive-off in the desired position. Drive-off situations may cause serious damage, such as collision, contact, damage to the structure, damage to pipes or well, etc.

1.4 DP Equipment Classes

According to IMO, there are three DP equipment classes that provide different levels of safety, redundancy, and station-keeping reliability (IMO, 1994; IMO, 2017). These are DP 1, DP 2, and DP 3 equipment classes. In some other sources, the DP 0 class also appears, which is considered a vessel installed with the DP system but not classified by a classification society.

DP 1 Equipment Class can be described as: in the event of a single failure in any ship's active components or system, there may be loss of position and/or heading. In other words, there is no redundancy.

DP 2 Equipment Class can be described as: in the event of a single failure in any ship's active components or system, loss of position and/or heading will not occur. Systems can include common static components that do not have an immediate impact or affect on the ability to maintain position in the event of failure. Examples of such components include ventilation and seawater systems that do not directly provide cooling for running machinery. Normally, these static components are not deemed to be prone to failure if they can exhibit sufficient protection against damage as demonstrated as per the administration's requirements. Single-failure criteria encompass various active components and systems, including generators, thrusters, switchboards, communication networks, remotely controlled valves, etc. Additionally, it includes any normally static components, including cables, pipes, manual valves, and so on, that may have an immediate impact on the ability to maintain position in the event of failure or if their protective measures are inadequately documented. It means there is redundancy if there is any problem in the event of a single failure, such as the loss of one generator, the loss of one of the thrusters, or a fault in one of the main engines. The DP 2 system can be considered a backup system, which will enable the DP system to still keep its position and heading to cease the operation and pull out safely and quickly.

DP 3 Equipment Class can be characterised as a state in which the occurrence of a single failure in any active or static components or system of a vessel does not result in the loss of position and/or loss of heading. DP 3 vessels have the same requirements as DP 2 vessels. Additionally, according to the requirements of DP 3 class, any normally static components are to be assumed to fail, and all components within any one watertight compartment should be protected from fire or flooding, as well as all components in any one fire sub-division that should be protected from fire or flooding.

The classification societies maintain standards and rules regarding the design and operation of vessels installed with a dynamic positioning system.

There are different identification codes used by classification societies to reflect the DP class notations. Table 1.1 shows some of the classification societies and how they use DP class notations.

Table 1.1 : Dynamic positioning class notations.

IMO	ABS	DNV	KR	LR	RINA	RS	TL
International Maritime Organization	American Bureau of Shipping (USA)	Det Norske Veritas (Norway)	Korean Register of Shipping (Korea)	Lloyds Register of Shipping (UK)	Registro Italiano Navale (Italy)	Russian Register of Shipping	Türk Loydu (Türkiye)
-	DPS-0	DPS 0 DYNAPOS-AUTS	DPS(0)	DP (CM)	DYNAPOS SAM	-	-
DP Class 1	DPS-1	DPS 1 DYNAPOS-AUT	DPS(1)	DP (AM)	DYNAPOS AM/AT	DYNPOS-1	DK1
DP Class 2	DPS-2	DPS 2 DYNAPOS-AUTR	DPS(2)	DP (AA)	DYNAPOS AM/AT R	DYNPOS-2	DK2
DP Class 3	DPS-3	DPS 3 DYNAPOS-AUTRO	DPS(3)	DP (AAA)	DYNAPOS AM/AT RS	DYNPOS-3	DK3

1.5 Capability Plot & Consequence Analysis

The DP capability plot is illustrated in Figure 1.7 and can be described as a theoretical plot sheet outlining the vessel’s capability to navigate specific environmental conditions, including wind, wave, and current from various directions. The capability plot shows how the vessel is able to keep her position without deviation depending on the vessel’s heading. Also, different thruster combinations can be calculated for the capability plot calculations. This function is designed to forecast the maximum weather conditions under which a vessel can effectively sustain its position and continue DP operations and show DPO the optimum heading for the best and safest operations.

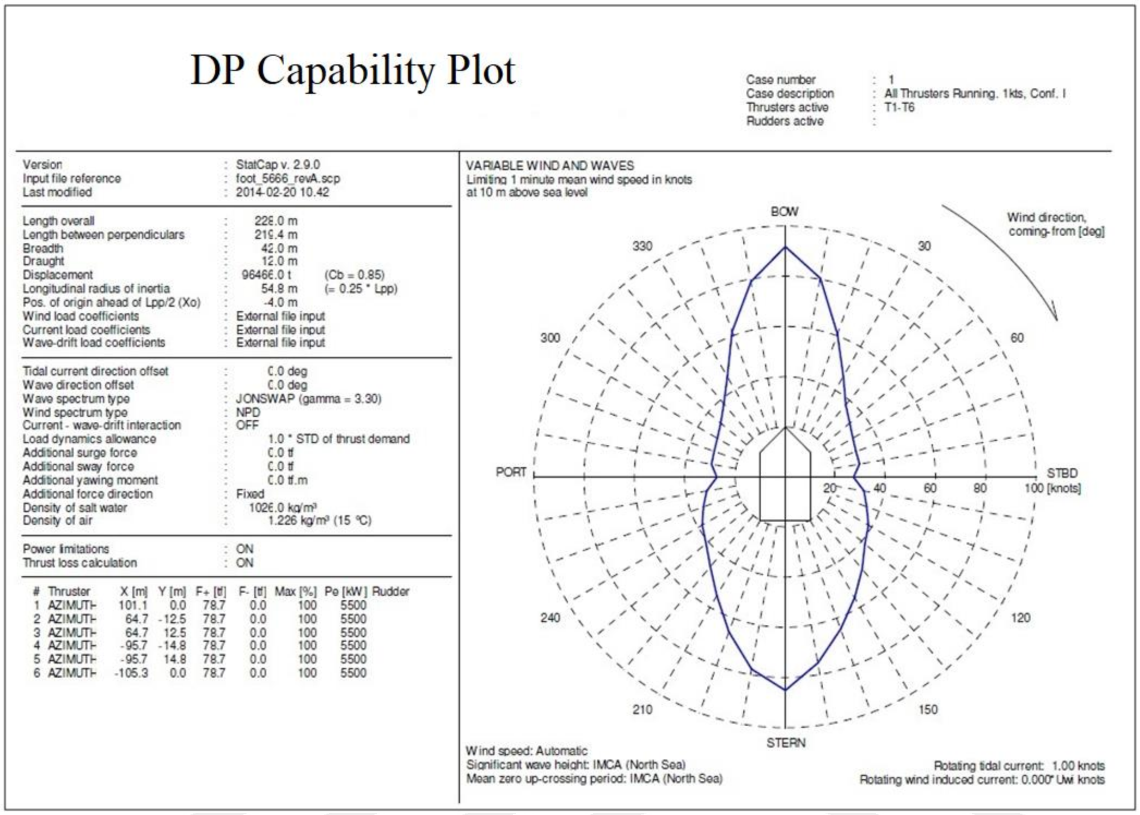

Figure 1.7 : An example of a DP capability plot (Kongsberg, 2022).

Another important feature of the DP system is defined as consequence analysis, which is a function of the system, conforming to the requirements of DP classes DP-2 and DP-3. This function engages in a constant process of conducting assessments in order to assess the vessel's capacity to maintain its position and heading under various failure conditions. It also examines the effects of predefined worst-case failures under existing weather and environmental conditions and the present system status for thrusters and power generation. Typical worst-case failures can be described as failure in the primary or most critical thruster, failure in a specific set of thrusters (one thruster group), or failure in a particular (one) power bus section. According to DNVGL-RP-E306 (2015, p. 24), the worst-case failure refers to the failure that exerts the most significant impact on the station-keeping capabilities. Typically, the identification of the worst-case failure is ascertained by means of conducting an FMEA study along with subsequent experimental trials.

1.6 Kalman Filtering

The DP system uses the Kalman filtering technique, which is a mathematical model of a vessel and its propulsion thruster system. The heading, position, and speed of the DP vessel are estimated by the extended Kalman filter technology in each of the three degrees of freedom, namely surge, sway, and yaw. It also includes algorithms for estimating the effects of sea currents and waves. The measurements for heading or position are compared with predicted or estimated data, which is generated by the mathematical model. The observed differences are subsequently employed to update the model. Figure 1.8 presents the configuration of the Kalman filter on the DP system.

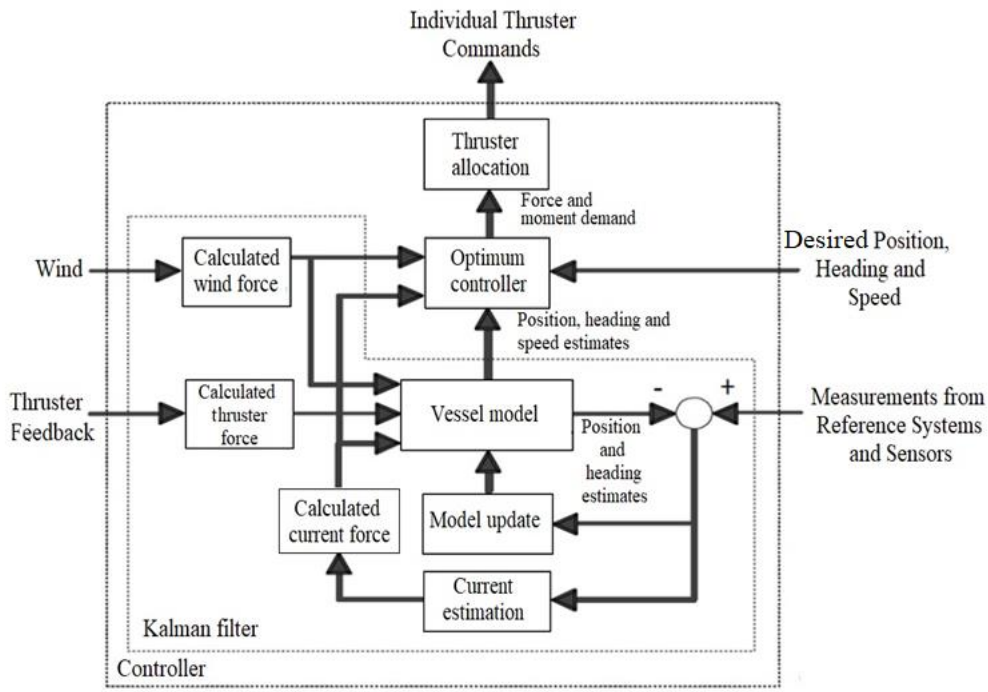

Figure 1.8 : Kalman filter configuration on DP system (Helvik, 1998).

The DP system is based on a mathematical vessel model that includes the specific ship's characteristics (current drag coefficients and virtual mass data). The mathematical model shows how the vessel will respond to an applied force, such as wind or thrusters. The extended Kalman filter uses a mathematical model. However, the model is not 100% accurate for real vessels, although the model is continuously corrected by the Kalman filtering technique.

1.7 Thruster Allocation

The DP system continuously calculates the actual force requirements in the alongside and athwart ship directions (directional force demand) and the required rotational moment (rotational moment demand). The thruster allocation function sends these force demands as pitch and/or rpm control signals to each thruster or propeller. Thus, the obtaining of the directional force and rotational moment required for the control of position and heading is achieved.

1.8 Offshore Vessel Types

The main parties involved with DP incidents are the vessels installed with the DP system that have a unique and significant role in all kinds of offshore operations such as drilling, diving, anchor handling, cable laying, supporting offshore platforms, etc. While performing these roles, DP vessels are required to keep their positions as reliable and precise as possible by using their system. A huge investment is made in offshore crew in order to maintain safety standards and minimise the risks. Consequences of serious accidents, such as a collision with a rig, loss of position by a drill ship, etc., may result in catastrophic events, causing the loss of lives and harm to the environment that may create financial and reputational difficulties for offshore operators and insurance companies. The types of offshore vessels installed with the DP system are provided below, in Table 1.2.

Table 1.2 : Types of offshore vessels.

Accommodation ship	Inspection, Maintenance, Repair Vessel (IMR)	ROV vessel
Anchor Handling Tug Supply (AHTS)	Jack-up	Seismic vessel
Cable lay vessel	Multi-Purpose Supply/Support Vessel (MPSV)	Semi submersible rigs
Crane vessel	Offshore barge	Shuttle tankers
Diving Support Vessel (DSV)	Offshore Construction Vessels (OCV)	Single Point Anchor Reservoir (SPAR)
Drill ship	Offshore Support Vessel (OSV)	Tension Leg Platform (TLP)
Floating platform	Pipe lay vessel	Well intervention vessel
FPSO	Platform Supply Vessel (PSV)	W2W (Walk to Work) vessel

2. LITERATURE REVIEW

Offshore operations are very risky, and the consequences of DP incidents can create catastrophic results due to the sensitivity of work such as drilling or diving. Although the DP system is an art of high technology, it may sometimes experience problems resulting in serious accidents. A certain risk of incidents caused by operational or technical errors always exists. These vessels may be involved in LoP (Loss of Position) incidents during DP operations. The consequences of such incidents may also affect human life and the environment. It is impossible to overstate the significance of conducting DP incident analysis and mining the probable causal links between incident prevention elements. A skilled dynamic positioning operator, also known as a DPO or DP operator, must therefore continuously monitor the system.

This Ph.D. thesis employs the Apriori algorithm to mine DP incident data from IMCA (International Maritime Contractors' Association) for 18 consecutive years (2004-2021). This study provides a complete analysis of the acquired strong rules and explores the potential relationship among their components. Additionally, it presents suggestions for mitigating the occurrences of DP incidents.

There have been many studies to investigate the causes of marine accidents by researchers. However, there is a lack of studies about the causes of dynamic positioning incidents.

According to related literature, studies about marine accidents mostly concentrate on human factors or ship-specific types. The analytical network process, human factor analysis, and classification system are examples of the approaches used to investigate the impact of human elements (Akyuz, 2017; Chen et al., 2013). These investigations demonstrate that human plays a significant role in the occurrence of marine accidents. According to these studies, the human component is a significant contributor to marine accidents.

Additionally, there are location-specific studies that analyse marine accidents only for specific locations. Raiyan et al. (2017) studied marine accidents by using the event tree analysis method to prove how a single factor could lead to an accident when combined with other factors or not. In their study, Erol, S. et al. (2018) conducted an investigation on marine accidents that happened in the Strait of Istanbul, employing the Neuro-fuzzy approach. The findings of this study demonstrate a positive correlation between adverse weather conditions and the severity of accidents, regardless of the size of the ship involved.

On the other hand, particular investigations provide the analysis not only geographically but also ship-specific types, their characteristics, and the results of such accidents. Mackovjak (2014) studied about the thesis with the title ‘‘Systems Theoretic Accident Analysis of an Offshore Supply Vessel Collision’’. Ugurlu and Yildiz (2016) have presented a paper on passenger ship accident analysis. The presence of a geographical correlation between passenger ship accidents and incidents involving other type of ships has been subject to investigation.

Ozaydin, E. et al. (2022) have studied a hybrid model for marine accident analysis utilising association rule mining (ARM) and Bayesian network (BN). The results, including the association rules, show the essential prerequisites for the emergence of accidents on fishing vessels. The outcomes of association rules demonstrate the minimum requirements for fishing boat accidents to occur. An investigation of contributory factors in 66 shipping accidents in Fujian water areas was studied by Weng and Li (2019).

Regarding the studies about association rule learning algorithms, Changhai and Shenping (2020) developed correlation factor mining in the maritime accidents database. Zhang and Liu (2011) conducted a similar research regarding the examination of the multi-dimensional association rule in a maritime casualty.

However, compared to marine accidents, the number of studies on dynamic positioning incidents is lower. The idea of dynamic positioning was first suggested and designed by an electrical engineer, whose name is H. Shatto, also known as the father of dynamic positioning (Breivik et al., 2015).

Through Shatto, the Eureka drillship was the world's first DP-installed vessel, which was automatically positioned in 1960. In the next few years, the DP system was first digitalized in 1968 onboard the Glomar Challenger vessel (Breivik et al., 2015). In terms of industry standards, the Sedco-445 vessel was promoted and introduced with the redundancy system for computers and position reference systems in 1971 (Jenssen, 2016). In the following years, the DP system was brought to Norway by Norwegian Professor Jens Glad Balchen, who provided a modern control theory for the industry without commercial interest. In Norway, he is widely recognised as the progenitor of engineering cybernetics (Jenssen, 2016; Breivik and Gunnar, 2009). Modern control theory consists of optimal control (a mathematical model), multivariable controls, and Kalman filtering.

In 1976, Balchen et al. presented the first Norwegian DP paper at the IFAC/IFIP Symposium on Automation in Offshore Oil Field Operations in Bergen, Norway. The present study is widely acknowledged as possibly being the first investigation into the application of Kalman filtering techniques in the context of dynamic positioning. In 1980, Professor Jens Balchen delivered an academic presentation on the subject of the dynamic positioning system, specifically focusing on its application through the use of Kalman filtering and optimal control techniques.

In addition to the above studies, Ismail et al. (2014) studied 219 DP incidents through descriptive statistics. It was found that crew training, discipline, and continual maintenance are critical components for DP units and operations.

Furthermore, nine recorded accidents that occurred over 16 years are investigated using analysis through the MTO (Man, Technology, and Organisation) to determine the root causes and weaknesses in safety barriers (2000–2015) by Dong et al. (2017). The MTO framework encompasses three distinct methodologies: structured analysis employing an event-and-cause diagram, change analysis elucidating deviations from previous occurrences or established norms, and barrier analysis aimed at finding deficient or non-existent administrative and technical challenges. The key finding indicates that a majority of accidents may be attributed to a confluence of technological, human, and organisational shortcomings. In this paper, mostly collision risk factors for the FPSO vessels and shuttle tankers have been studied.

Next, Jenssen and Hauge (2002) studied DP performance and incident analysis. Moreover, Haugen and Smogeli (2017) have studied the safety requirements of dynamic positioning systems with regards to system architecture, equipment, and redundancy.

As aforementioned in the previous pages, there is still a long way to go to analyse the dynamic positioning incidents and their causes. Hauff (2014) contributed a comprehensive research study on the LoP incidents for DP vessels for his Master thesis. In this study, the Bayesian Belief Networks analysis was utilized. Another study proposed by Azad (2014) presented the criticality analysis of the platform supply vessel, which reflects the possible root causes of DP accidents. Regarding situational awareness and DPO decision-making, The study conducted by Overgard, K., et al. (2015) examined significant incidents that occurred in the context of dynamic positioning operations. The paper revealed more about the human factor aspect of DP incidents. The paper revealed more about the human factor side of dynamic positioning-related incidents. Additionally, the study conducted by Chae (2017) focuses on the use of formal safety assessment in the context of human mistakes occurring in incidents related to dynamic positioning of vessels. More broadly, the reasons for failures in dynamic positioning systems were investigated by Pil in 2018. Moreover, Olubitan and Loughney (2018) investigated the statistical analysis of the DP occurrences and failures that are related to dynamic positioning systems. The study focused on the main and initiating causes, specifically loss of position incidents. The findings indicate a rise in occurrences over the spring and summer periods. Also, the results reveal that diving support vessels, pipe lay vessels, and drill ships are the most common vessel types involved in incidents. Based on the investigation, a total of 152 incidents were consistently outlined. According to the analyses, the primary factors contributing to incidents were identified as the position reference and thruster systems in the period ranging from 2000 to 2016.

On the other hand, the investigation conducted by Sanchez et al. (2021) focused on the application of binary logistic regression modelling to forecast the occurrence of position loss in dynamic positioning drilling operations. The probability of an excursion from the desired position has been determined using DP incidents during drilling operations.

According to Chae and Jung (2015), the dynamic positioning system is comprised of seven essential components, including the thruster system, power system, DP computer, human-machine interface, sensors, position reference system, and DP operator. Loss-of-position incidents onboard DP vessels are commonly attributed to errors within seven distinct criteria. The objective of this study is to identify and analyse safe operational practices for dynamic positioning by examining both qualitative and quantitative data on DP loss of position accidents reported to the International Marine Contractors Association on an annual basis. This study examines a total of 612 cases of DP LoP accidents that were reported between years 2001 and 2010. The primary objective of this analysis is to identify the principal factors contributing to these accidents and to ascertain their respective frequencies. Consequently, errors related to position reference systems have the greatest occurrence rates involving DP elements. The subsequent components included the DP computer, human error, power system, and thruster system. Following the analysis of PRS, the flowchart was generated in a collaborative process with experts engaging in brainstorming activities. Furthermore, the examination of conditional probability has been conducted using a Bayesian network. It can be inferred that drive-off incidents were mostly attributed to the utilisation of DGPS, microwave radar, and HPR. This study employed Bayesian networks to identify the primary factors contributing to DGPS errors. Some of the causes include failure of electric components, blockage of signal, errors in relative mode, signal failure, and signal weakness.

The significance of secondary causes, such as substandard design, insufficient maintenance, inadequate procedures or inadequate testing, and incomplete commissioning, lies in their inherent association with human factors. The process of attributing an extra secondary cause, such as electrical issues, is straightforward and can be readily categorised. Nevertheless, even in such instances, the root causes of the failure may still stem from human factors. This emphasises the necessity of conducting a thorough investigation into the technical and human elements behind the DP incidents in question. The future direction of the event analysis effort should prioritise this aspect.

Additionally, despite advancements in switchboards, generators, and power management systems, the occurrence of electrical and partial blackouts persists.

The frequency of accidents and the utilisation of dynamic positioning technology have exhibited a growing pattern in the last decade. This phenomenon may contribute to the observed rise in reported occurrences of blackouts, encompassing both complete and partial power failures. Additionally, the limited disposal of DP vessels might further account for this escalation. However, Fisher (2006) observes a significant rise between the years 1999 and 2000.

The objective of Hogenboom's (2021) study is to assess the disparities among different dynamic positioning operations conducted on the Norwegian Continental Shelf (NCS) and their impact on the cognitive tasks executed by the DP operator. The findings of the Applied Cognitive Task Analysis (ACTA) conducted on the five operational types within the DP domain, namely supply vessels, shuttle tankers, flotels, construction support vessels, and drill ships, indicate that there are no significant variations in the cognitive tasks performed by the dynamic positioning operators across these different vessel types. These operational types' contexts, however, are significantly varied, and these distinctions have an impact on cognitive processes.

Both incidents and accidents are selected for use in the MTO study. The definitions of them and other important terms are given here to provide a consistent and clear understanding. According to Rausand (2011), an accident can be characterised as an abrupt, undesired, and unanticipated occurrence or series of occurrences that results in detrimental consequences to individuals, the environment, or other valuable resources. An incident may be defined as an unanticipated and unpredictable occurrence that has the potential to cause damage or injury to one or more assets. Based on the definitions provided, it can be inferred that an accident is a specific type of occurrence whereby harm is inflicted against assets. Furthermore, the concept of a near accident may be described as an incident that occurs unexpectedly and without prior anticipation and has the potential to do harm to one or many assets but ultimately does not. The term 'near accident' refers to an incidence that is distinct from an accident. The word 'near miss' is used synonymously with the concept of an incident that slightly avoids becoming an accident.

There are only a few studies pertaining to strong association rules for DP loss of position incidents that have been published. This study examines the factors that contribute to DP incidents, specifically drift-off and drive-off LoP incidents.

As of today, there are several regulatory bodies and organisations involved in addressing the various aspects of dynamic positioning design, including the establishment of rules, regulations, standards, and the provision of training for significant crew members.

- International Maritime Organisation (IMO)
- International Marine Contractors Association (IMCA)
- Dynamic Positioning Committee (DPC)
- The Nautical Institute (NI)
- Classification Societies

These organisations are responsible for generating guidelines that are specifically aimed at enhancing safety and operational efficiency in relation to dynamic positioning. Firstly, IMO developed a guideline pertaining to vessels equipped with dynamic positioning systems in 1994 (MSC/Circ.645). While the IMO circulars provide the minimum requirements for DP vessels, the IMCA provides more comprehensive guidance. IMCA is recognised as a prominent international trade organisation that represents a significant proportion of contractors and the related supply chain within the offshore marine construction sector. The organisation also conducted a risk analysis pertaining to the collision of dynamically positioned support vessels with offshore structures.

The mission of DPC is to promote the sharing of knowledge, technical discussion, training, and education, encourage the improvement of DP reliability, establish guidelines, and resolve any other issues relating to dynamic positioning that help incident-free execution of DP operations and are consistent with marine technology society's objectives (DPC website, 2020). DPC also provides technical and operational guidance notes, design guidelines for DP vessels, and guidance for DP personnel.

On the other hand, the NI describes the training and certification requirements of DP operators and officers. Today, any officer or engineer who works onboard DP-installed vessels has to go through the NI DP training scheme to become a fully certified DP operator onboard.

Additionally, the Dynamic Positioning Training Executive Group (DPTEG) comprises the following organisations: Its primary objective is to foster effective communication and ensure that the NI DP operator training scheme remains aligned with the evolving requirements of the industry.

- International Support Vessel Owners' Association (ISOA)
- International Marine Contractors Association (IMCA)
- Oil Companies International Marine Forum (OCIMF)
- International Association of Drilling Contractors (IADC)
- International Chamber of Shipping (ICS)
- Regional Training Providers (RTPs)

There are just a few examples of studies in the literature related to strong association rules for DP loss of position incidents. This Ph.D. thesis investigates the factors affecting DP incidents, particularly drift-off and drive-off LoP incidents. It should be emphasised that this study will provide specific rules and valuable insights into the relationships between variables that contribute to DP incidents. Consequently, this thesis possesses the potential to serve as groundbreaking research in the field of maritime safety pertaining to dynamic positioning vessel operations.

3. METHODOLOGY

3.1 Data Collection

The primary objective of this doctoral thesis is to undertake a comprehensive investigation of the potential factors contributing to DP incidents by using the Apriori algorithm in conjunction with association rule mining. The study utilised data sourced from the IMCA database and the annual reports on DP incidents. This database has a comprehensive collection of 1352 DP incidents and undesired events that occurred throughout the period spanning from 2004 to 2021.

First of all, a total of 1352 DP incidents have been statistically analysed to reveal the main and secondary factors behind the incidents. The present study is structured in the following manner, with a focus on the system architecture.

Data preparation > Data cleaning > Modelling of association rules learning > Generation of frequent itemsets > Generation of strong association rules > Analysis of strong association rules (Changhai and Shenping, 2020).

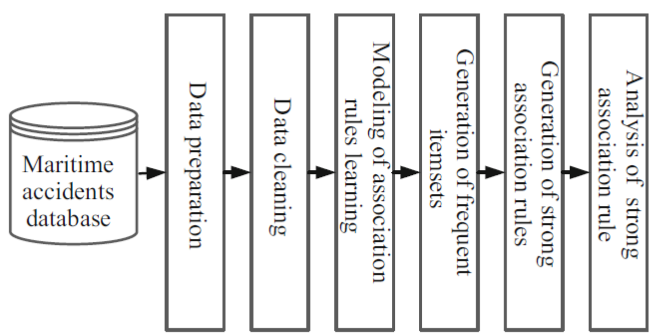

Figure 3.1 : Mining process of DP incidents using association rule.

After filtering the dataset, 691 DP incidents have been used to discover association rules due to the sufficient data contained in the reports.

The primary objective of this study is to conduct association rule mining in order to get insights into the factors affecting DP vessel incidents. The results of the research provide a reference for the offshore industry to improve training and operational requirements and reduce the occurrence of DP incidents before they happen. The major dominating cause that resulted in DP incidents has been found to be thrusters and propulsion failure. The second significant cause has been identified as the human factor, and the third greatest cause has been the computer in the last 18-year period.

3.2 Association Rule Mining (Apriori Technique)

Association analysis is effective when finding significant relationships concealed in large datasets. Those relationships may usually be defined by association rules. Through this study, further effective and preventive measures can be developed to help reduce the number of DP incidents, relying on the use of association rules between the factors contributing to the occurrences of dynamic positioning incidents. Consequently, the association rule approach was developed in order to investigate the relationship between contributing elements and identify patterns in this study among DP incidents of different levels of severity.

The Weka programme was utilised to conduct an analysis of datasets and identify strong association rules. According to Garner (1995), Weka may be described as a machine-learning workbench. The software in question has been created by the University of Waikato, located in New Zealand. It is an open-source machine learning tool that has been validated. It offers convenient accessibility through a graphical user interface, standard terminal applications, or a Java application programming interface (Frank et al., 2005). It is commonly used in teaching, research, and industrial uses and includes a variety of integrated resources for standard machine learning tasks.

3.2.1 Step 1: data preparation

The process of data preparation has three main stages: data selection, data processing, and data transformation. The IMCA DP incidents database provided a dataset consisting of 1352 dynamic positioning incidents that happened between 2004 and 2021.

Data selection is the process of extracting a specific collection of data from the original information sourced from IMCA based on the requirements and preferences of users. The technique of data pre-processing involves the removal of missing data as well as the generation or deletion of duplicate records. The primary objective of data transformation is to identify and extract meaningful features from the dataset, aligning with the specific goals of the work at hand, in order to effectively portray the data.

3.2.2 Step 2: data cleaning

The IMCA database contains a substantial volume of data, some of which has inadequate information, hence impeding its use in the analytical process. To enhance the acquisition of association rules, any missing or duplicate data has been eliminated. After filtering the dataset, 691 DP incidents have been found with sufficient data for further analysis. Although classify and clustering algorithms have been performed using 691 attributes, the Apriori algorithm has been performed using 691 attributes due to the data integrity and settings of the algorithm.

3.2.3 Step 3: modelling of association rules learning

Causation model of DP incidents is established, which includes main and secondary causes, root (trigger) causes, incident type (drift-off, drive-off, loss of redundancy), PRS usage, operation type, etc.

3.2.4 Step 4: generation of frequent itemsets

The initial step involves generating the candidate set Ck, which comprises the items that have the potential to become frequent itemsets. Next, the calculation of the support value is performed using the candidate set Ck, which allows for the determination of the frequent itemset Lk.

3.2.5 Step 5: generation of strong association rules

The generation of all simple association rules is based on frequent itemsets, and these association rules are picked to form a strong association rules set, with the condition that they exceed the minimum confidence thresholds provided by the user.

3.2.6 Step 6: analysis of strong association rules

The analysis focuses on the examination of learned strong association rules, the exploration of their internal interaction with DP incidents, and the investigation of the casual relationship among incidents.

4. ANALYSIS AND DISCUSSIONS

4.1 Statistical Overview of DP Incidents

Following the IMCA records, there are twelve (F) codes that can be defined as a main or secondary cause for DP incidents. Table 4.1 defines each code and its descriptions.

Table 4.1 : Main causes of DP incidents as per F codes (IMCA, 2021).

Codes	Main causes of DP Incident	Description
F1	Computer	Fault on computer's hardware or software
F2	Electrical	Fault on electrical switchboard, UPS, voltage
F3	Environment	Excessive wind, wave, swell, current
F4	External factors	3rd parties interference, other vessels
F5	Human factor	DP Operator's faults
F6	PRS	Fault on PRS, satellites, signals, etc.
F7	Power	Fault on generators or PMS
F8	Sensors	Fault on sensors (Gyro, MRU, Wind sensor)
F9	Thrusters/Propulsion	Faults on thrusters, controls, propulsion, rudder, etc.
F10	Mechanical	Mechanical failure
F11	Undetermined	When main or secondary cause is not identified
F12	Procedures	Insufficient procedures, SMS, checklists, etc.

It is also crucial to understand that vessel operators use three distinct categories when reporting a DP incident to the IMCA. In the beginning, IMCA used the following criteria (2004 and 2005):

i. Loss of position 1: any major loss of position
ii. Loss of position 2: any minor loss of position
iii. Lost time incident: any downtime through loss of redundancy, no loss of position (like DP undesired event)

Since 2006, the IMCA has utilised five distinct categories of DP incidents for reporting purposes.

4.1.1 DP incident

A DP incident refers to the occurrence of a loss of automated dynamic positioning control, a loss of vessel position, or any other incident that has led to, or should have led to, the declaration of a ‘red alert’ status.

4.1.2 DP undesired event

DP undesired event refer to the occurrence that lead to a disruption in maintaining stability or other unforeseen and uncontrolled incidents. These events either resulted in or should have triggered a state of heightened vigilance known as a ‘yellow alert’ status.

4.1.3 DP downtime

DP downtime refers to an issue pertaining to the maintenance of a position or the loss of redundancy. This issue does not reach the severity of a ‘red alert’ or ‘yellow alert’. However, it does lead to a temporary suspension of operational activities owing to the need for investigation, rectification, testing, and similar procedures, resulting due to the loss of confidence in the dynamic positioning system.

4.1.4 DP near-miss

The term ‘‘DP near miss’’ refers to an event that has negatively impacted the performance, redundancy, or reliability of a dynamic positioning system but has not developed into a full-fledged ‘‘DP incident’’, ‘‘undesired event’’, or ‘‘down-time’’. An example of a DP near-miss condition can be scintillation or a crane interfering with the Fanbeam or Artemis line of sight.

4.1.5 DP hazard observation

DP hazard observation refers to the identification of a collection of circumstances that possess the capacity to escalate to a state of near-miss or more severe incidents. An example of such a circumstance is the placement of a Fanbeam laser target on handrails situated along a heavily trafficked walkway, where crew members wearing PPE decorated with retro-reflective tape are present. The second example can refer to a crane-lift that is swung in close proximity to the line of sight of Artemis.

According to the marine department of the IMCA, the DP downtime categorization was in 2016 to DP observation. Hence, both titles are considered to be the same. At present, the IMCA has reached a consensus on the clarification of dynamic positioning incidents into three distinct categories.

i. A DP incident refers to a significant incident characterised by a major system failure, either caused by environmental or human error, leading to the loss of DP capability.
ii. A DP undesired event refers to a significant breakdown inside a system, either due to environmental or human error, resulting in the loss of redundancy and/or compromised DP capability.
iii. A DP observation can refer to a particular situation that does not exhibit any loss of redundancy or compromise in the operating capability of the DP system. However, it is still considered sufficiently noteworthy to be shared.

The IMCA DP station-keeping event scheme requires the reporter to provide both a main and secondary cause of the event. The main cause is the event that caused the vessel to lose redundancy or position-keeping ability; the secondary cause is the reason why that main cause occurred. Different from other studies, this Ph.D. thesis also provides trigger and initiating factors that have been analysed to reveal the hidden causes behind the incidents. In this thesis, DP incidents and DP undesired events have been taken into consideration during statistical calculations since both events have significant results, such as loss of position (drift-off or drive-off) or loss of redundancy. Consequently, both definitions are covered by the same term, which will thereafter be called DP incidents. A total of 1352 DP incidents that occurred between 2004 and 2021 were examined and sorted according to the main cause and incident year. The categorization has been highlighted in Table 4.2 below.

Table 4.2 : Main causes of DP incidents occurred between 2004 and 2021.

Incident \ Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total
Computer	1	8	4	18	22	8	6	14	8	6	13	13	15	17	22	9	16	28	199
Electrical	1	4	6	5	10	10	12	3	4	0	0	1	0	5	3	5	2	1	70
Environment	2	3	4	4	3	2	4	5	2	3	2	11	0	4	1	3	8	5	59
External Factors	0	0	1	1	1	0	1	0	2	0	2	0	1	2	1	0	1	1	13
Human factor	6	5	13	7	5	10	3	3	11	7	7	10	16	3	9	4	7	0	120
PRS	12	5	9	13	27	17	21	8	6	13	9	6	7	9	13	11	8	20	182
Power	8	4	8	11	9	13	5	7	6	13	9	10	15	10	15	23	33	21	191
Sensors	0	0	0	0	0	1	0	1	5	2	3	5	0	2	5	0	2	1	26
Thruster Propulsion	4	7	3	8	21	12	2	13	20	20	26	24	24	21	37	39	43	53	320
Mechanical	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Undetermined	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	3
Procedures	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	4
Total	34	36	48	67	102	75	56	54	64	64	71	80	78	73	106	94	120	130	1352

According to the data shown in Table 4.2, it is found that (F9) thrusters/propulsion has been the main cause since 2012. Secondly, (F1) computer and (F7) power-related incidents have been identified as other significant main causes. Furthermore, empirical evidence has demonstrated a gradual increase in the overall number of DP incidents during the last decade. In addition to the data provided, Figure 4.1 illustrates the trend for the main causes of DP incidents over the last 18 years period (2004 and 2021).

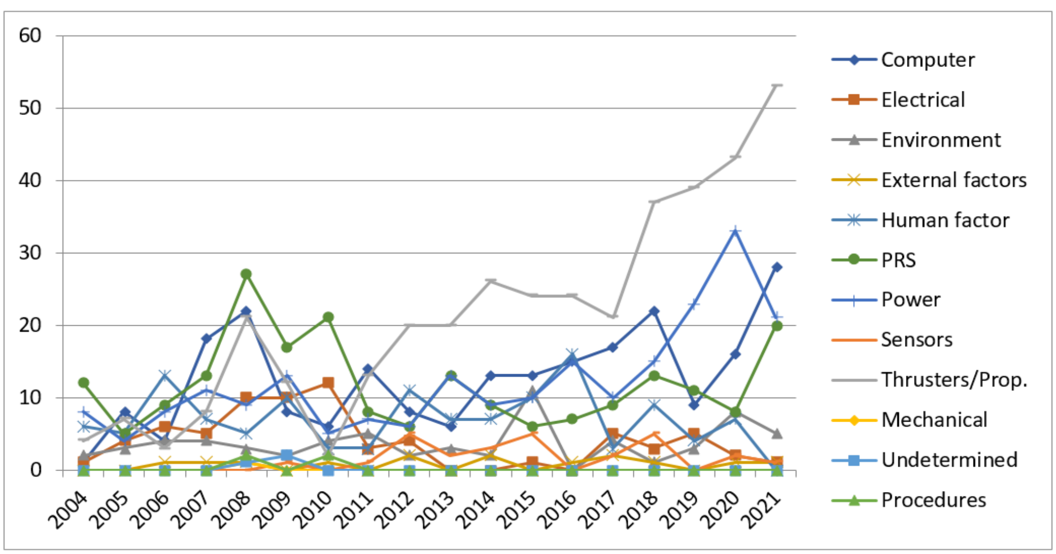

Figure 4.1 : Trend for the main causes of DP incidents between 2004-2021.

The examination of the event trend associated with the DP incident trend further demonstrates that a significant percentage of incidents may be attributed to thrusters and propulsion failures as the main cause. Computer-related problems have been identified as the second main cause. The main contributing causes have been power, position reference sensors, and human factors, respectively. Another noteworthy finding is the rapid and gradual increase in the thrusters/propulsion factors (F9) during the past five-year period.

4.2 Statistical Analysis of Recent Data

The rapid advancement of the technology has led to a perceived underestimation of the significance of human elements. On the contrary, the role of the human plays a more critical role during the utilisation of hi-tech systems and equipment. Following the year 2016, it can be observed from the aforementioned findings that the human component is predominantly considered a secondary or trigger cause rather than a main cause. To receive the most updated and reliable information from the DP incident statistics, the last five-year period has been taken into consideration to compare the main causes and secondary causes. In the last five years, the most common main causes that resulted in DP incidents have been as thrusters and propulsion failures. The next most significant main causes have been identified as computer and position reference system-related failures. Table 4.3 illustrates data from the last five years regarding the secondary causes of DP incidents.

Table 4.3 : Secondary causes of DP incidents occurred between 2017 and 2021.

Incident \ Year	2017	2017*	2018	2018*	2019	2019*	2020	2020*	2021	2021*	Total DP Incidents	Total* Undesired Events	Total
Computer	1	0	1	5	1	5	5	9	3	17	11	36	47
Electrical	0	11	7	22	1	29	5	39	5	23	18	124	142
Environment	0	0	0	0	0	1	2	0	2	0	4	1	5
External Factors	1	1	1	5	2	4	1	0	1	1	6	11	17
Human Factor	6	4	8	12	12	25	18	7	29	10	73	58	131
PRS	0	0	0	1	0	1	1	1	3	4	4	7	11
Power	0	2	0	3	0	0	0	2	2	8	2	15	17
Sensors	0	0	0	1	0	0	0	0	0	3	0	4	4
Thruster/Propulsion	1	2	1	4	3	4	1	1	4	3	10	14	24
Mechanical	0	0	0	0	0	0	3	14	3	9	6	23	29
Procedures	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	9	20	18	53	19	69	36	73	52	78	134	293	427

According to the results, the primary secondary causes identified are electrical and human factors, followed by electrical and computer-related failures. Figures 4.2 and 4.3 further illustrate the prevalence of the human factor as a secondary cause in DP incidents.

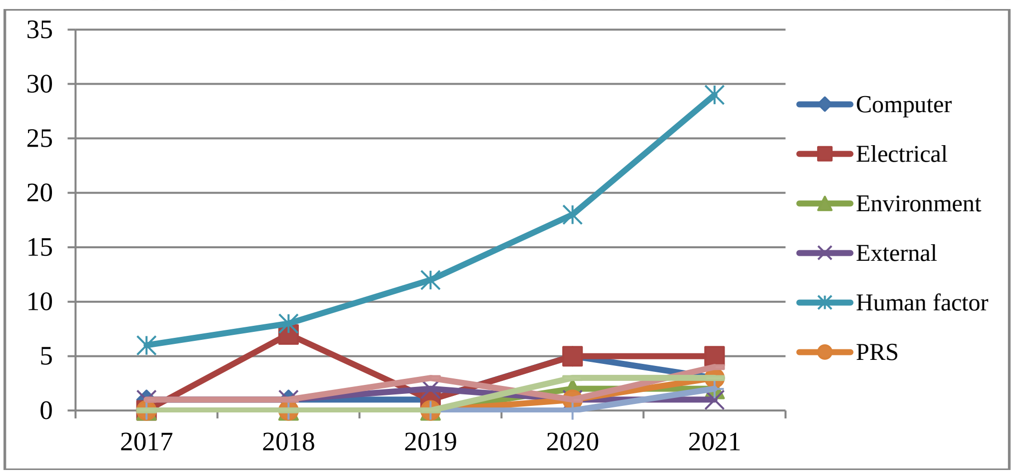

Figure 4.2 : Secondary causes of DP incidents (2017–2021).

The rate of DP incidents attributed to human-related secondary causes was determined to be 54.5% throughout the last 5-year period (2017–2021). Considering the combined occurrences of both DP incidents and DP undesired events, it is seen that the proportion of DP incidents attributed to human-related secondary causes is found to be 30.6%.

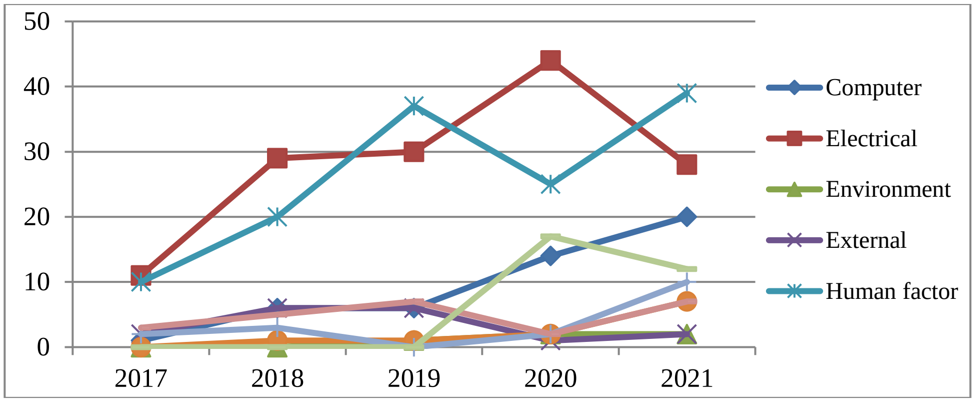

Figure 4.3 : Secondary causes of DP incidents & undesired events (2017–2021).

In addition to main and secondary causes, human factors might be triggered by additional sub-factors, referred to as ‘trigger factors’ or ‘initiating factors’. These factors can be listed as pressing an incorrect button, accidentally pressing the button, incorrect command, communication failure, poor design, lack of knowledge, and lack of bridge team management. Given that dynamic positioning operations are controlled by DPOs, there has been a careful examination of the human factor to precisely identify the main and secondary causes it may stimulate. Figure 4.4 illustrates the secondary causes and trigger factors that are grouped under the main causes of human factor.

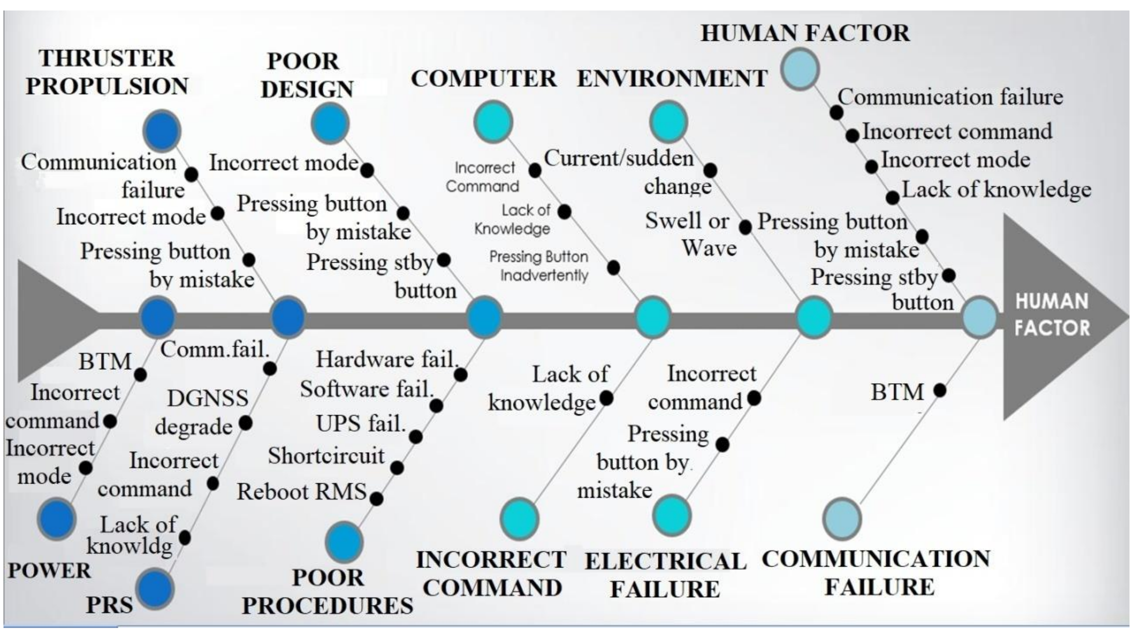

Figure 4.4 : Trigger (initiating) factors of human.

Last but not least, various types of ship and operation have been recorded in the event of DP incidents, as seen in Table 4.4. Based on the data shown in the table, it can be observed that DP incidents mostly happen during specific operations, including diving (17.3%), drilling (16.4%), ROV operations (14.6%), cargo operations (12.5%) , and pipe lay (7.7%) operations.

Table 4.4 : DP incidents as per operation type (2004-2021).

Type of Ship/Operation	Number of DP Incidents	% Percentage
Diving	130	17.3%
Drilling	123	16.4%
ROV	110	14.6%
Cargo	94	12.5%
Pipe lay	58	7.7%
Stand by	42	5.6%
Offshore Load/Offtake	39	5.2%
Other	22	2.9%
Cable lay	20	2.7%
Other	114	15.2%

4.3 Apriori Algorithm (Association Rules) Analyses

There are several algorithms used for the analysis and mining of large datasets. Apriori is considered the most recognised and commonly used algorithm, that having been first introduced by Agrawal and Srikant (1994). The primary objective of the Apriori algorithm is to generate association rules characterised by high confidence levels, hence indicating the accuracy of the rule. It is used to reveal more complex associational relationships between the factors. The Apriori algorithm is a straightforward method used for extracting frequently occurring trends from large datasets in order to identify common itemsets and associations among different item sets.

By using the Weka programme, to perform an effective analysis, classifying and clustering are used before creating association rules by using the Apriori algorithm.

In general, the algorithms used in this paper are listed below.

i. Classify > functions: LibSVM, Multilayer Perception
ii. Classify > lazy: IBk
iii. Classify > trees: J48
iv. Cluster > Simple K-Means
v. Associate > Apriori

In this study, there are seven attributes selected to perform analysis. All attributes are planned to have a nominal value. Table 4.5 illustrates the attributes used in Weka.

Table 4.5 : Attributes utilized in Weka.

Factor (Attributes)	Item
Main cause	All F codes (Fig. 2)
Secondary cause	All F codes (Fig. 2) + other factors
Trigger	All F codes (Fig. 2) + other factors
Incident type	Loss of position (LoP), Loss of redundancy (LoR)
Drift-off / Drive-off	Drift-off, Drive-off, No
Different PRS online	Yes, No
Ops Status	Drill, Diving, Supply, Pipe lay, ROV, etc.

Next, there are four steps to be applied in the Weka programme, as follows:

i. Pre-process: Upload the appropriate dataset in arff format.
ii. Classify: Instances (attributes) are classified by four different algorithms.
iii. Clustering: To cluster by using the K-means algorithm.
iv. Association analysis has been applied by using the Apriori algorithm.

After uploading the DP incident dataset, classification has been applied by four different function algorithms, which are multilayer perception, LibSVM, Lazy IBK, and trees J48. Afterward, clustering was performed by the K-means algorithm. The cluster approach is employed to categorise a set of items that exhibit similar traits. Weka offers a wide range of methods for executing cluster analysis, with the simple k-means approach being particularly popular.

4.3.1 Classify

A confusion matrix has been derived by using the trees J48 algorithm, which provides the most accurate result. The J48 method is commonly employed for the purpose of classifying various applications and achieving precise outcomes in the classification process (Saravanan and Gayathri, 2018). A success rate of 80% has been achieved. The results show the accuracy of the software in identifying the main causes of DP incidents based on the entire dataset. Figure 4.5 shows the confusion matrix result obtained by using the trees J48 algorithm.

```
=== Confusion Matrix ===

   a   b   c   d   e   f   g   h   i   <-- classified as
  93   1   1   0   5   0   3   0   2 |   a = Computer
   2   5   0   0   1   1  11   0   4 |   b = Electrical
   0   0  42   0   3   2   2   0   0 |   c = Environment
   0   0   1   0   0   0   1   0   3 |   d = ExternalFactors
   0   0   3   0  72   2   0   0   0 |   e = HumanFactor
   6   0   1   0   4 100   5   1   4 |   f = PRS
   0   9   0   0  17   3 107   0  10 |   g = Power
   1   0   1   0   0   3   1  18   1 |   h = Sensors
   3   1   2   0   6   6  17   0 164 |   i = Thruster/Prop
```

Figure 4.5 : Confusion matrix created using trees J48 algorithm.

Another matrix that has been derived by using the treesJ48 algorithm is DP incident types. The accuracy rates of 99% demonstrate the correct differentiation between the loss of position and loss of redundancy situations, as seen in Figure 4.6. The method demonstrates its efficacy in determining whether an occurrence will lead to loss of position (LoR) or loss of redundancy (LoR) based on the antecedents.

```
=== Confusion Matrix ===

   a   b   <-- classified as
 385   0 |   a = LoPos
   1 365 |   b = LoRed
```

Figure 4.6 : Confusion matrix created using the trees J48 algorithm.

4.3.2 Cluster

For clustering, the Simple k-means algorithm has been used to show a similar trend within the entire data set. This technique employed in this part utilises the Euclidean distance measure to calculate the distances between instances and clusters.

It is a simple unsupervised learning algorithm. The dataset is divided into groups based on similarity (Bansal, 2021). The clustering of groups is depicted in Figures 4.7, 4.8, and 4.9 as shown below.

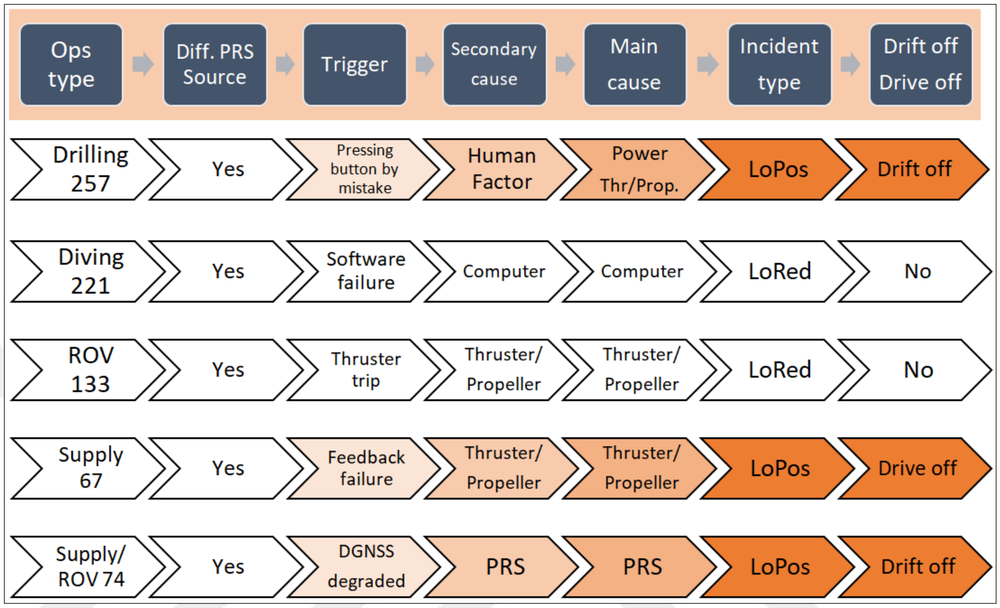

Figure 4.7 : Clustered groups (1).

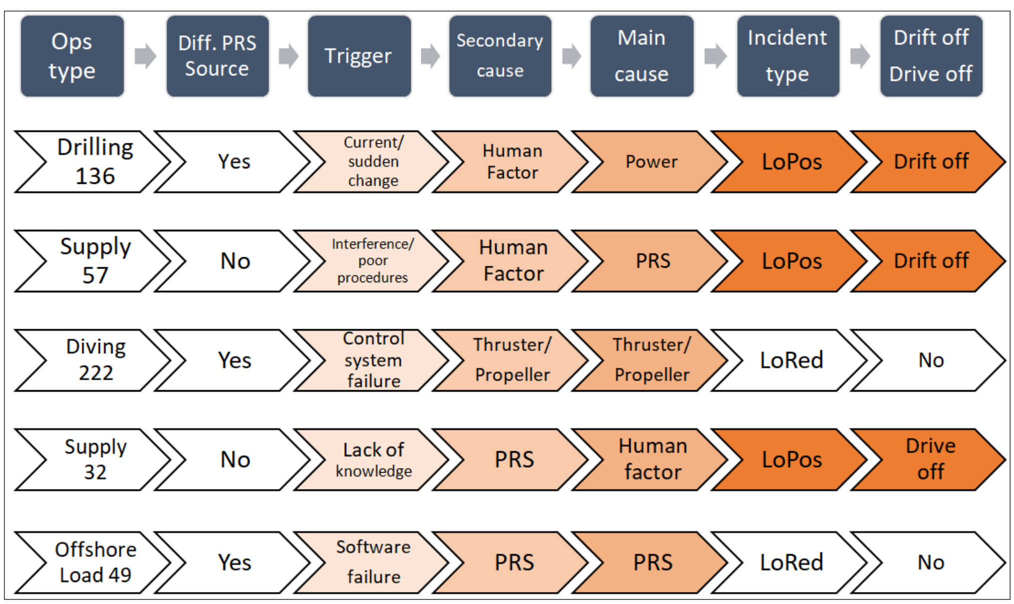

Figure 4.8 : Clustered groups (2).

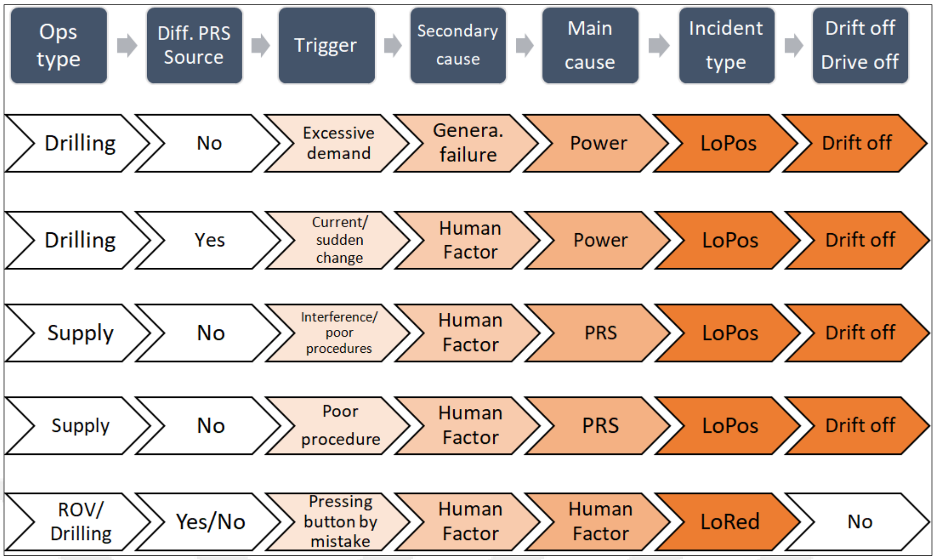

Figure 4.9 : Clustered groups (3).

The Figures provided above show significant results of the study, especially the common relationships among each factor and their consequences. These trends can also be taken as a reference to understand the process and consequences of events. Based on the observed trends, it can be inferred that the human element serves as a prominent factor contributing to the secondary causes of DP incidents, which are triggered by human errors. Other trending factors have been observed as thrusters and propellers or the factors associated with PRS (position reference systems).

Additionally, it can be revealed that loss of position incidents occur more frequently than loss of redundancy. A total of 691 DP incidents from the IMCA database have been chosen as the training set for association rule mining. However, there were a total of 385 loss of position (LoP) incidents and 367 loss of redundancy occurrences (LoR). Table 4.6 displays the distribution of DP incidents, with 324 cases classified as drift-off incidents and 61 cases classified as drive-off incidents.

Table 4.6 : Summary of DP incidents.

LoP (Loss of Position) Incidents (385)		LoR (Loss of Redundancy) Incidents (367)
Drift-off	Drive-off	Loss of redundancy (367)
324 (84%)	61 (16%)	(48%)

4.3.3 Strong association rules

In order to perceive the causes and effects of DP incidents as well as relationships between antecedents and consequences, the ARM (Association Rule Mining) method has been applied by using Weka open-source machine learning software. Association rule mining aims to reveal knowledge and relationships from large datasets. An analytical description of the association rule can also be defined in the form (Agrawal and Srikant, 1994);

$X \Rightarrow Y$, where $X, Y \subseteq I$, $X \cap Y = \emptyset$. The association rule $X \rightarrow Y$ suggests that the occurrence of Y is dependent on the occurrence of X. In the context of association rules, X is referred to as the antecedent, representing the item(s) that precede the occurrence of another item(s) denoted as Y, which is known as the consequent.

The support of the association rule $X \Rightarrow Y$ reflects the probability that item X and item Y happen together simultaneously (in the entire data set). The support of an association rule is quantitatively defined as the ratio of the number of transactions in the entire dataset that contain both $X \cup Y$, to the total number of transactions in the dataset. This may be mathematically represented as:

$$\text{Support }(X) = \|\{t \in D \mid X \subseteq t\}\| / \|\{t \in D\}\|$$

$$\text{Support }(X \cup Y) \geq \text{minimum support (threshold)}$$

Support is the frequency of occurrence. In example, if the support is 20%, (x) and (y) occur together in always 20% of cases.

The confidence of the conditional probability that item Y will happen on the condition that item X happens. It is called conditional probability. This may be mathematically represented as:

$$\text{Confidence }(X \Rightarrow Y) = \text{support }(X \cup Y) \, / \, \text{support }(X)$$

$$\text{Confidence }(X \cup Y) \geq \text{minimum confidence (threshold)}$$

Figure 4.10 provides a comprehensive summary of the methods used to calculate support and confidence values.

$$support(X \rightarrow Y) = \frac{|\{b_i | b_i \in X \wedge b_i \in Y\}}{\sum_{i=0}^{m} b_i}$$

$$confidence(X \rightarrow Y) = \frac{support(X \cup Y)}{support(X)}$$

Figure 4.10 : Analytical description of support and confidence (Cakir et al., 2021).

Since there are a great number of these association rules that meet the criteria of support and confidence, filtering and ranking of found rules are provided by the ‘lift’ factor. Lift displays the confidence of the rule to the past likelihood of subsequent, and it is the result of dividing rule confidence by rule support. It is used to measure the importance of a rule. The lift of an association rule can be shown in the form of:

$$\text{Lift } (X \Rightarrow Y) = \text{support } (X \cup Y) \,/\, (\text{support } (X) \text{ support } (Y))$$

Generally, the higher the lift results, the stronger the association between the items. The result of the lift factor is supposed to be higher than 1. When the lift value is equal to 1, it indicates that there is no association of between variables X and Y. When the lift value exceeds 1, it indicates a positive correlation between variables X and Y. However, in the event that the lift value remains below 1, it indicates the presence of a negative association between the elements, suggesting that they are unlikely to occur together.

The user specifies a minimal support threshold, denoted as *min_sup*, and a minimum confidence threshold, denoted as *min_conf*, before conducting the process of association rule learning. The set of itemsets with a support value greater than or equal to the minimal support threshold, referred to as “a frequent item” or large itemset, is denoted as *Lk*. It represents the collection of all frequent k-itemsets.

The association rule learning process consists of two distinct stages. In the initial phase, the algorithm identifies all the frequent itemsets that possess a support value that is higher or equal to the specified minimum support threshold, denoted as *min_sup*.

During the second step, the system produces association rules, computes their confidence levels, and selects association rules that have a confidence level that is higher or equal to the specified minimum confidence thresholds, denoted as *min_conf*.

The Apriori algorithm is a well-established method used in the field of data mining for the purpose of identifying frequent itemsets in association rule mining. The technique employs an iterative approach known as layer-by-layer search, where k-itemsets are utilised to investigate (k+1) items. Firstly, the algorithm identifies a collection of frequently occurring 1-itemsets. The set is represented by the symbol L1. L1 is used to identify the collection of frequent 2-itemsets, denoted as L2, and subsequently, L2 is utilised to discover L3, and this process continues iteratively until the frequent k-itemsets can no longer be ascertained.

Conviction is further employed as a metric to assess the degree of independence between variables X and Y. The concept of conviction involves assessing the likelihood of event X occurring independently of event Y by comparing it to the observed frequency of event X occurring without event Y. In contrast to the confidence metric, conviction takes into account both X and Y and consistently assumes a value of 1 when the corresponding items are entirely unconnected. Therefore, if the conviction value is 1 or close to 1, it is understood that X and Y items are completely unrelated.

In the next stage, association rules have been listed with the strongest lift values. It pertains to the ratio between the confidence of a given rule and the anticipated confidence of such a rule. From Table 4.7 to Table 4.16, the strong association rules for possible DP incidents, the antecedents (left-handed) and consequences (right-handed), are illustrated based on the strongest confidence values. In the Weka Apriori algorithm calculations, a total of 691 attributes have been used due to data integrity and the settings of the algorithm.

Table 4.7 : Weka analysis settings (1).

Weka language code	weka.associations.Apriori -N 100 -T 0 -C 0.5 -D 0.05 -U 1.0 -M 0.1 -S -1.0 -c -1
Attributes (4)	Root_Cause, Sec_Cause, Main_Cause, Incident
Minimum support	0.05
Minimum metric <confidence>	0.5

Table 4.8 : Strong association rules (1).

Rule ID	Antecedent		Consequent	Conf	Lift	Conv
1	Root_Cause=FeedbackFailure 43	==>	Main_Cause=Thruster_Prop 43	1.0	3.65	31.2
2	Root_Cause=ThrusterTrip 40	==>	Main_Cause=Thruster_Prop 40	1.0	3.65	29.0
3	Root_Cause=DGNSSdegraded 45	==>	Main_Cause=PRS 43	0.96	5.68	12.4
4	Sec_Cause=SoftwareFailure 43	==>	Main_Cause=Computer 37	0.86	6.12	5.2
5	Main_Cause=Environment 47	==>	Incident=Drift_off 38	0.81	1.9	2.7
6	Root_Cause=ControlSystemFailure 47	==>	Main_Cause=Thruster_Prop 36	0.77	2.8	2.8
7	Main_Cause=HumanFactor 66	==>	Incident=Drift_off 50	0.76	1.78	2.2
8	Sec_Cause=HumanFactor 107	==>	Incident=Drift_off 79	0.74	1.74	2.1
9	Sec_Cause=ElectricalFailure 81	==>	Incident=LoR 60	0.74	1.51	1.8
10	Sec_Cause=PoorProcedures 15	==>	Incident=Drift_off 10	0.67		

Table 4.9 : Weka analysis settings (2).

Weka language code	weka.associations.Apriori -N 100 -T 0 -C 0.6 -D 0.04 -U 1.0 -M 0.02 -S -1.0 -A -c -1
Attributes (4)	Root_Cause, Sec_Cause, Incident
Minimum support	0.01
Minimum metric <confidence>	0.6

Table 4.10 : Strong association rules (2).

Rule ID	Antecedent		Consequent	Conf	Lift
1	Root_Cause=Current_SuddenChanges Sec_Cause=HumanFactor 7	==>	Incident=Drift_off 7	1.0	2.35
2	Root_Cause=PressStand_bybutton Sec_Cause=HumanFactor 5	==>	Incident=Drift_off 5	1.0	2.35
3	Root_Cause=ThrusterTrip Sec_Cause=ElectricalFailure 8	==>	Incident=LoR 8	1.0	2.04
4	Root_Cause=AuxSystFailure Sec_Cause=AuxSystFailure 5	==>	Incident=LoR 5	1.0	2.04
5	Root_Cause=OS_Failure Sec_Cause=OS_Failure 21	==>	Incident=LoR 19	0.9	1.84
6	Root_Cause=ControlSystemFailure Sec_Cause=ElectricalFailure 10	==>	Incident=LoR 9	0.9	1.83
7	Root_Cause=PressingButtonbyMistake Sec_Cause=HumanFactor 30	==>	Incident=Drift_off 24	0.8	1.88
8	Root_Cause=FeedbackFailure Sec_Cause=ElectricalFailure 10	==>	Incident=LoR 8	0.8	1.63
9	Root_Cause=ThrusterTrip Sec_Cause=ThrusterTrip 31	==>	Incident=LoR 24	0.77	1.58
10	Root_Cause=ControlSystemFailure Sec_Cause=ControlSystemFailure 28	==>	Incident=LoR 20	0.71	1.45
11	Root_Cause=LackofKnowledge Sec_Cause=HumanFactor 17	==>	Incident=Drift_off 12	0.71	1.66
12	Root_Cause=ElectricalFailure Sec_Cause=ElectricalFailure 10	==>	Incident=LoR 7	0.7	1.42
13	Root_Cause=HydraulicSystemFailure Sec_Cause=HydraulicSystemFailure 10	==>	Incident=LoR 7	0.7	1.42

It has been revealed that DP-2 and DP-3 vessels usually are equipped with an extra set of equipments as a result of the redundancy requirements. This provides DP operators with the chance to allocate more time to address the problem or relocate from the operational location to a safer area in order to rectify the issue.

Table 4.11 : Highlight of strong association rules associated with human factor.

Rule ID	Antecedent		Consequent	Conf	Lift
1	Root_Cause=Current_SuddenChanges Sec_Cause=HumanFactor 7	==>	Incident=Drift_off 7	1.0	-
2	Root_Cause=PressStand_bybutton Sec_Cause=HumanFactor 5	==>	Incident=Drift_off 5	1.0	-
3	Root_Cause=PressingButtonbyMistake Sec_Cause=HumanFactor 30	==>	Incident=Drift_off 24	0.8	-
4	Root_Cause=LackofKnowledge Sec_Cause=HumanFactor 17	==>	Incident=Drift_off 12	0.71	-

Table 4.12 : Weka analysis settings (3).

Weka language code	weka.associations.Apriori -N 100 -T 0 -C 0.5 -D 0.05 -U 1.0 -M 0.0 -S -1.0 -A -c -1
Attributes (5)	Ops, Root_Cause, Sec_Cause, Main_Cause, Incident
Minimum support	0.1
Minimum metric <confidence>	0.5

Table 4.13 : Strong association rules (3).

Rule ID	Antecedent		Consequent	Conf	Lift
1	Root_Cause=IncorrectCommand Main_Cause=HumanFactor 9	==>	Incident=Drift_off 9	1.0	2.35
2	Root_Cause=PressStand_bybutton Main_Cause=HumanFactor 6	==>	Incident=Drift_off 6	1.0	-
3	Root_Cause=Current_SuddenChanges Sec_Cause=HumanFactor Main_Cause=Environment 6	==>	Incident=Drift_off 6	1.0	-
4	Sec_Cause=HumanFactor Main_Cause=Environment 13	==>	Incident=Drift_off 13	1.0	2.35
5	Root_Cause=Squalls Main_Cause=Environment 9	==>	Incident=Drift_off 9	1.0	2.35
6	Sec_Cause=Environment Main_Cause=Thruster_Prop 5	==>	Incident=Drift_off 5	1.0	-
7	Root_Cause=ControlSystemFailure Sec_Cause=ControlSystemFailure Main_Cause=Power 7	==>	Incident=LoR 7	1.0	2.04
8	Root_Cause=ThrusterTrip Sec_Cause=ElectricalFailure Main_Cause=Thruster_Prop	==>	Incident=LoR 8	1.0	2.04
9	Root_Cause=AuxSystFailure Main_Cause=Thruster_Prop 7	==>	Incident=LoR 7	1.0	2.04
10	Root_Cause=FuelSystFailure Sec_Cause=FuelSystFailure Main_Cause=Power 5	==>	Incident=LoR 5	1.0	2.04
11	Root_Cause=MechanicalFailure Sec_Cause=MechanicalFailure Main_Cause=Thruster_Prop 5	==>	Incident=LoR 5	1.0	2.04
12	Root_Cause=ThrusterTrip Main_Cause=Thruster_Prop 40	==>	Incident=LoR 33	0.82	1.67
13	Sec_Cause=ElectricalFailure Main_Cause=Thruster_Prop 39	==>	Incident=LoR 33	0.82	1.67
14	Sec_Cause= HumanFactor Main_Cause= HumanFactor 28	==>	Incident=Drift_off 23	0.82	1.93

Table 4.14 : Highlight of strong association rules associated with human factor.

Rule ID	Antecedent		Consequent	Conf	Lift
1	Root_Cause=IncorrectCommand Main_Cause=HumanFactor 9	==>	Incident=Drift_off 9	1.0	-
2	Root_Cause=PressStand_bybutton Main_Cause=HumanFactor 6	==>	Incident=Drift_off 6	1.0	-
3	Root_Cause=Current_SuddenChanges Sec_Cause=HumanFactor Main_Cause=Environment 6	==>	Incident=Drift_off 6	1.0	-
4	Sec_Cause=HumanFactor Main_Cause=Environment 13	==>	Incident=Drift_off 13	1.0	-
5	Root_Cause=Squalls Main_Cause=Environment 9	==>	Incident=Drift_off 9	1.0	-

The findings of the study indicate that environmental factors play crucial role and exert a substantial influence on the losing position of the DP vessel. Therefore, it is recommended to incorporate meteorology training combined with DP operations, including procedures for responding to emergencies through diverse and severe weather conditions (squalls, solitons, currents, etc.), in order to adequately prepare all DPOs.

It is also known that in the event of unexpected squalls impacting the vessel's position, there exists a significantly enhanced likelihood of a drift-off incident. Maintaining continuous watchkeeping and closely monitoring meteorological conditions are crucial aspects while keeping DP watches.

Additionally, blackout recovery training has considerable significance for DPOs. It is expected that all DP operators and engine room operators to acquire the necessary knowledge and understanding of their own vessel's specific characteristics, as well as the procedures and time frame involved in recovering from a blackout situation.

Table 4.15 provides a concise overview of potential incidents, allowing for a quick examination of their effects and consequences via an analysis of the root causes. The occurrence of drift-off incidents can be attributed to antecedents of human error, including pressing the standby button or any button by mistake, incorrect commands, and a lack of knowledge. Secondly, the presence of environmental factors such as squalls, unpredictable swells and waves, currents, and rapid changes significantly increases the likelihood of drift-off incidents.

Table 4.15 : Strong association rules (4).

Rule ID	Antecedent		Consequent	Conf	Lift
1	Root_Cause=Squalls 9	==>	Incident=Drift_off 9	1.0	2.35
2	Root_Cause=PressStand_bybutton 6	==>	Incident=Drift_off 6	1.0	2.35
3	Root_Cause=ImproperWiring 5	==>	Incident=Drift_off 5	1.0	2.35
4	Root_Cause=OS_Failure 24	==>	Incident=LoR 22	0.92	1.87
5	Root_Cause=Swell_Wave 12	==>	Incident=Drift_off 11	0.92	2.16
6	Root_Cause=ThrusterTrip 40	==>	Incident=LoR 33	0.82	1.68
7	Root_Cause=Current_SuddenChanges 25	==>	Incident=Drift_off 20	0.8	1.88
8	Root_Cause=UPS_Failure 15	==>	Incident=LoR 12	0.8	1.88
9	Root_Cause=PressingButtonbyMistake 39	==>	Incident=Drift_off 31	0.79	1.87
10	Root_Cause=IncorrectCommand 13	==>	Incident=Drift_off 10	0.77	1.81
11	Root_Cause=HardwareFailure 25	==>	Incident=LoR 18	0.72	1.47
12	Root_Cause=ControlSystemFailure 47	==>	Incident=LoR 33	0.7	1.43
13	Root_Cause=FuelSystFailure 20	==>	Incident=LoR 14	0.7	1.43
14	Root_Cause=HydraulicSystemFailure 20	==>	Incident=LoR 14	0.7	1.43
15	Root_Cause=AuxSystFailure 10	==>	Incident=LoR 7	0.7	1.43
16	Root_Cause=ExcessivePowerDemand 10	==>	Incident=Drift_off 7	0.7	1.43
17	Root_Cause=LackofKnowledge 24	==>	Incident=Drift_off 16	0.67	1.57

Furthermore, Table 4.16 presents visual representation of the strong association rules pertaining to the operation type, vessel types, and consequent incidents.

Table 4.16 : Strong association rules (5).

Rule ID	Antecedent		Consequent	Conf	Lift
1	Ops=Shuttle_FPSO Sec_Cause=HumanFactor 9	==>	Incident=Drift_off 9	1.0	2.35
2	Ops=Shuttle_FPSO Root_Cause=PressingButtonbyMistake 6	==>	Incident=Drift_off 6	1.0	2.35
3	Ops=Diving, Sec_Cause=Blackout Main_Cause=Power 5	==>	Incident=Drift_off 5	1.0	2.35
4	Ops=Diving Root_Cause=OS_Failure 6	==>	Incident=LoR 6	1.0	2.04
5	Ops=Cable_Pipelay Sec_Cause=HumanFactor 7	==>	Incident=Drift_off 7	1.0	2.35
6	Ops=Drilling, Sec_Cause=ElectricalFailure Main_Cause=Thruster_Prop 6	==>	Incident=LoR 6	1.0	2.04
7	Ops=Drilling Root_Cause=ThrusterTrip Main_Cause=Thruster_Prop 5	==>	Incident=LoR 5	1.0	2.04
8	Ops=PSV_Cargo Root_Cause=ControlSystemFailure Sec_Cause=ElectricalFailure 6	==>	Incident=LoR 6	1.0	2.04
9	Ops=ROV Root_Cause=ControlSystemFailure Sec_Cause=ControlSystemFailure 6	==>	Incident=LoR 6	1.0	2.04
10	Ops=ROV Sec_Cause=OS_Failure Main_Cause=Computer 6	==>	Incident=LoR 6	1.0	2.04
11	Ops=PSV_Cargo Root_Cause=HardwareFailure Main_Cause=Computer 5	==>	Incident=LoR 5	1.0	2.04
12	Ops=PSV_Cargo Root_Cause=ThrusterTrip Sec_Cause=ThrusterTrip 5	==>	Incident=LoR 5	1.0	2.04

The aforementioned findings provided above highlight the various categories of offshore vessels and the most common types of incidents experienced. DPOs who are employed onboard specific DP vessels can focus on specific concerns, hence ensuring preparedness for preventive actions in advance.

The attributes outlined in Table 4.5 are utilised for the implementation of the Apriori algorithm, which is employed to derive strong association rules from the comprehensive dataset of DP incidents.

The tables presented above show the strong association rules, antecedents, and consequences with the strongest confidence values. Several different settings have been applied to analyse the dataset.

4.4 Analyses for the Loss of Position Incidents

In the context of offshore DP incidents, it is widely acknowledged that incidents involving loss of positions (LoP) incidents, specifically drift-off and drive-off incidents have more significance and yield more substantial results compared to incidents involving loss of redundancy (LoR). Consequently, accidents associated with loss of position are accorded greater attention and seriousness within the industry. The factors causing LoP incidents have been investigated individually with respect to each type of ship or operation. A comprehensive dataset has a total of 385 instances of loss of position (LoP) incidents. During these incidents, the vessels experienced a loss of their position-keeping ability, leading to unintentional changes in their positions due to drift-off or drive-off. There were a total of 324 instances of LoP incidents that resulted in drift-off, whereas 61 instances of LoP incidents resulted in drive-off. Consequently, in order to enhance precision, each operation type has been divided and investigated individually.

4.4.1 Drift-off incidents

Based on the investigation conducted, it has been determined that there are a total of 324 drift-off incidents occurring during various operations. Out of these 324 incidents, it has been noted that 92 cases occurred without the presence of an alternative source of PRS. In contrast, 201 cases were observed on vessels that employed redundancy measures, hence utilising several sources for PRS. (There are uncertainties regarding the redundancy or variety of PRS systems onboard other 31 drift-off incidents.)

It is important to note that the collection of drift-off incidents that occurred during major operations may be categorised as follows: drilling (20%), ROV (13%), pipelay/cablelay (13%), and diving operations (12.6%). The overall incidence of these four categories amounts to 58.6% of all drift-off incidents (LoP), surpassing the majority of the entire incidences.

Besides, the rate of drift-off incidents occurring during cargo operations is 10.8%, W2W operations are 5.2%, while shuttle tankers and FPSO operations demonstrate an even lower rate of 4.6%. The overall rate of drift-off incidents is reported to be 79.2%, with the remaining 20.8% of records attributed to other types of operations, such as standby operations, cementing operations, and ploughing operations that were not included due to the limited number of incident data available.

4.4.1.1 Drilling

Among the 324 occurrences of drift-off incidents, a total of 65 cases (20%) were specifically categorised as drift-off incidents, occurring during drilling operations onboard drill ships. Among the 65 instances of drift-off examined, it was observed that 47 occurrences involved the use of alternative sources of PRS, whilst nine cases did not use a separate source for PRS. Consequently, these particular DP vessels did not have any redundancy. Last but not least, nine of them were categorised as unidentified. According to Figure 4.11, a majority of drill ships (72%) employed alternative sources of PRS and had redundancy, similar to the approach adopted in diving operations. Nevertheless, it is important to acknowledge that the presence of variety in PRS did not serve as the main contributing factor for the occurrences of drift-off incidents. The utilisation of an alternative PRS source is deemed imperative in light of its redundancy and the requirements of enhanced operational safety. It does not exclusively prevent occurrence of drift-off incidents. However, it is considered a significant precaution for preventing drive-off incidents.

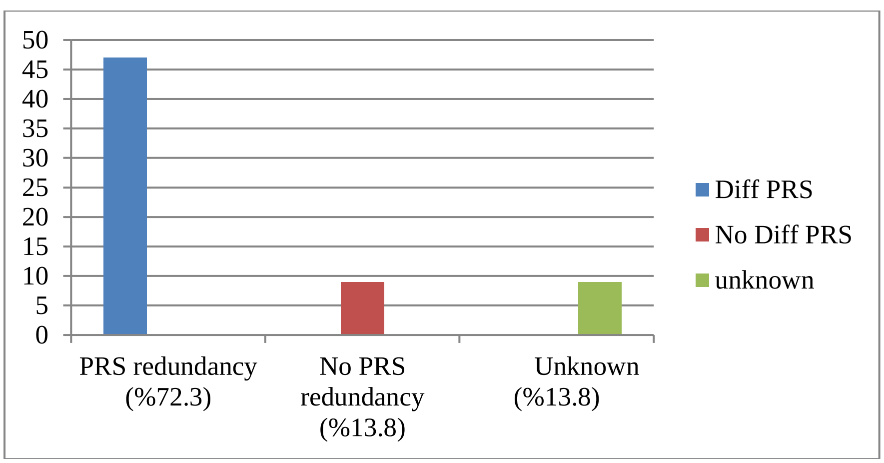

Figure 4.11 : Selection of different PRS for drill ships/operations.

After conducting a thorough examination of the factors that contribute to drift-off incidents on drill ships, a comprehensive analysis of 65 drift-off cases reveals the main causes. Among these cases, the majority can be attributed to the following factors: Power-related failures account for 26 cases (40%), environmental factors account for 11 cases (17%), human factors account for eight cases (12.3%), thruster and propulsion failures account for eight cases (12.3%), and PRS-related failures account for five cases (7.6%). Figure 4.12 presents the distribution of the main causes for drill ships.

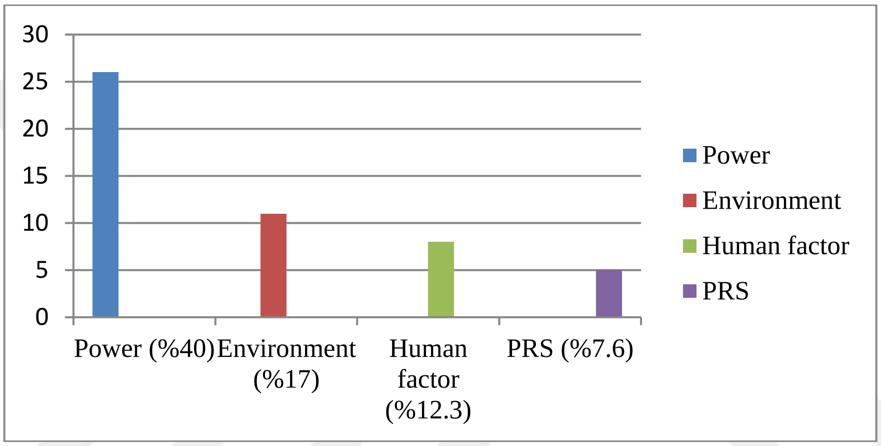

Figure 4.12 : Main causes of drift-off incidents on drill ships/operations.

When considering the main causes related to power-related failures, it is obvious that generator failures exhibit the highest prevalence as a secondary cause, representing 27% (7 cases). When considering solely secondary causes, the following are predominantly identified: 15 cases (23%) attributed to human factors, nine cases (13.8%) associated with environmental factors, seven cases (10.7%) attributed to generator failures, seven cases (10.7%) attributed to thruster propulsion issues, and four cases (6.1%) attributed to electrical failures, as illustrated in Figure 4.13.

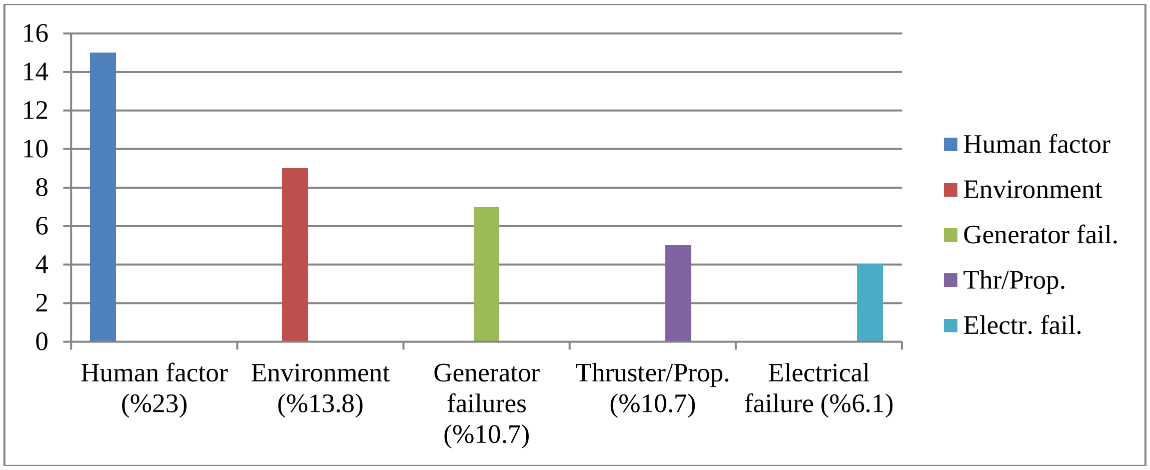

Figure 4.13 : Secondary causes of drift-off incidents on drill ships/operations.

In the analysis of environmental causes and their interactions with human factors (as a main or secondary cause), nine cases involve the environment as a secondary cause, while three cases involve the environment a main cause. The occurrence of 12 drift-off cases have been triggered mostly as follows: six cases (50%) attributed to current or sudden changes in the weather conditions, three cases (25%) attributed to squalls, two cases (16.6%) attributed to swells or waves, and one case (8.3%) attributed to lightning. Figure 4.14 shows the distribution of environmental-related trigger factors that caused drift-off incidents. Lessons learned from the findings encompass the need of efficient watchkeeping, diligent monitoring the DP system, and significance of adverse weather conditions that empower DPOs to proactively respond.

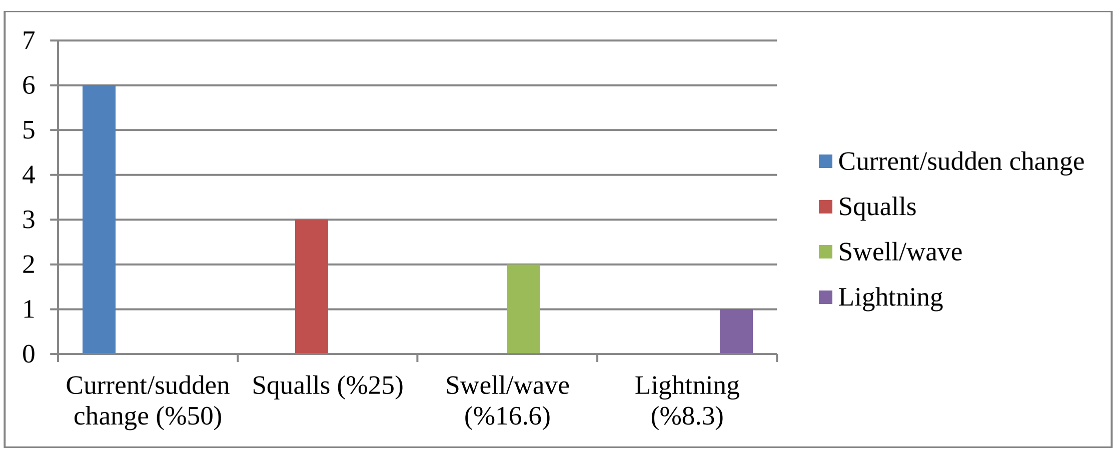

Figure 4.14 : Trigger factors for environmental-related drift-off incidents.

In the investigation of 17 incidents involving human factors (15 cases in which human factors play a role as a secondary cause, two cases with human factors as the main cause), the majority of these drift-off incidents were triggered by the following means: There were six drift-off cases (35.2%) triggered by accidentally pressing the button, two cases (11.7%) resulting from a lack of knowledge, and two cases (11.7%) caused by incorrect command or incorrect mode, as seen in Figure 4.15.

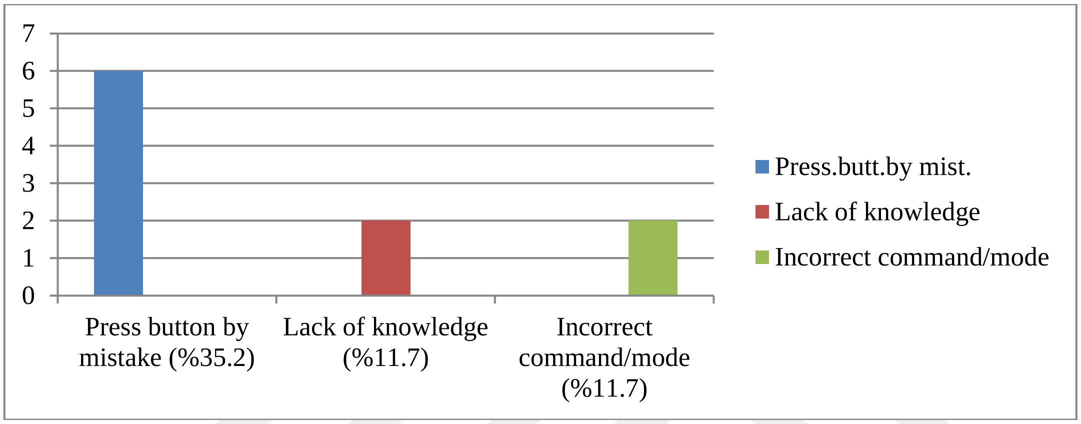

Figure 4.15 : Trigger factors for human factor related drift-off incidents.

4.4.1.2 ROV Operations

Among the 324 occurrences of drift-off incidents, 42 cases (13%) were identified as drift-off incidents that took place specifically during ROV operations. Among the 42 drift-off cases examined, it was observed that 19 cases involved the use of alternative sources of PRS, while 22 cases did not use an alternative source for PRS, resulting in the lack of redundancy. Lastly, one of them was recorded as unidentified. Figure 4.16 illustrates the utilisation of PRS during ROV ship operations.

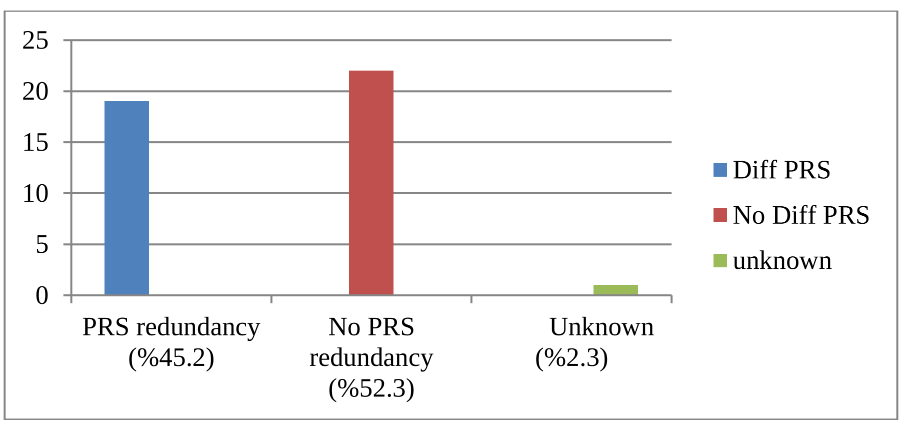

Figure 4.16 : Selection of different PRS for ROV ships/operations.

An investigation was conducted to identify the main causes contributing to drift-off incidents during ROV operations. Among the 42 recorded drift-off cases, it was found that human factor-related failures accounted for nine cases (21.4%). Similarly, nine cases (21.4%) were attributed to failures related to thruster and propulsion systems. Power-related failures were responsible for eight cases (19%), while PRS-related failures accounted for another eight cases (19%). Notably, six of the PRS-related failures were a result of relying solely on a single system without utilising multiple sources. The findings are depicted in Figure 4.17.

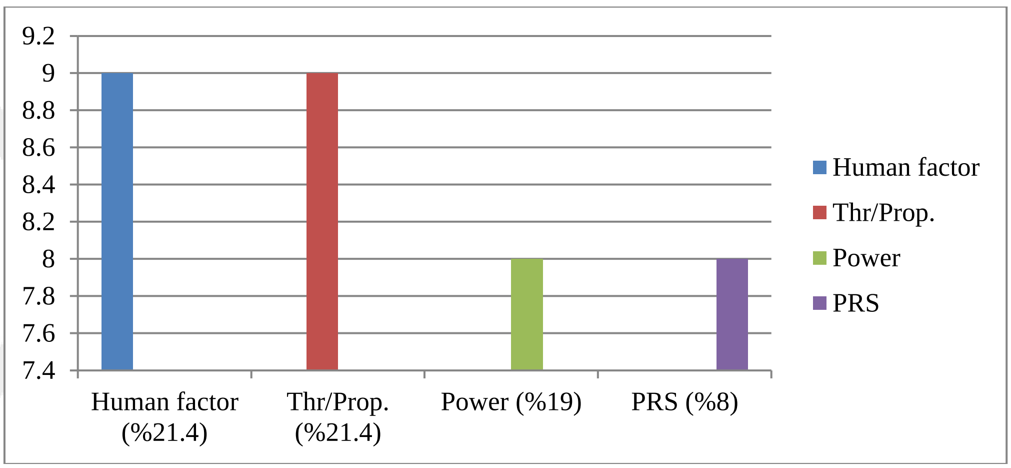

Figure 4.17 : Main causes of drift-off incidents on ROV ships/operations.

When considering only the secondary causes, it is obvious that the majority of these causes may be attributed to 16 cases (38%) resulting from human factors, and six cases (14.2%) resulting from thruster propulsion failures, as seen in Figure 4.18.

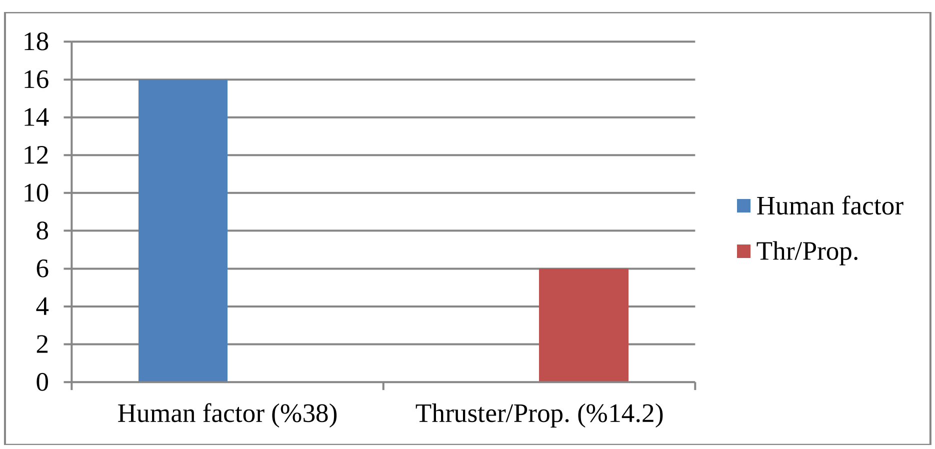

Figure 4.18 : Secondary causes of drift-off incidents on ROV ships/operations.

In the investigation 18 incidents involving human factors (15 cases in which human factors play the role as a secondary cause, three cases with human factor as the main cause), the majority of these drift-off incidents were triggered by the following means: There were seven drift-off cases (38.8%) triggered by accidentally pressing the button or pressing the standby button, three cases (16.6%) caused by poor bridge team management, and two cases (11.1%) resulting from a lack of knowledge. The distribution of trigger factors for human-related drift-off incidents can be seen in Figure 4.19. There is a significant observation indicating that the occurrence of drift-off incidents attributed to human factors is associated with a 38.8% incidence of pressing the wrong button by mistake.

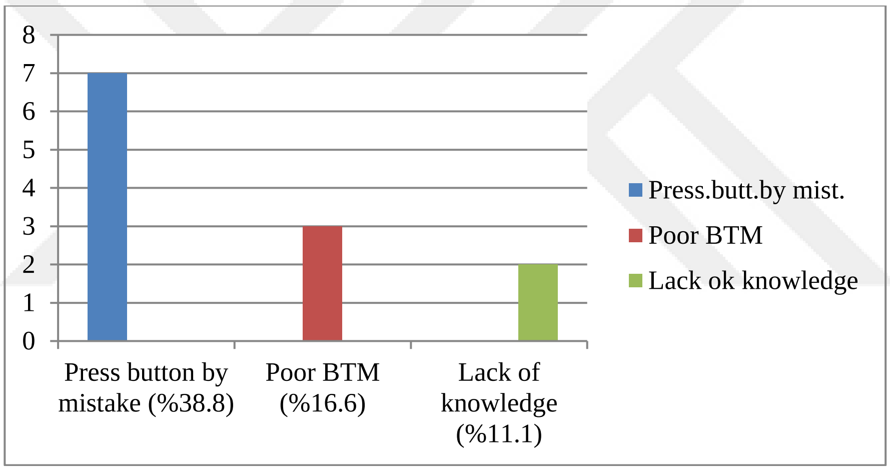

Figure 4.19 : Trigger factors for human factor related drift-off incidents.

In the investigation of incidents involving drift-off associated with the thruster and propulsion failures (specifically, nine cases where thruster and propulsion were identified as the main cause), it has been observed that the majority of these nine drift-off cases are triggered by the following factors: four cases (44.4%) were a result of thruster trips, two cases (22.2%) were caused by human error such as accidentally pressing the button or incorrect command, and two cases (22.2%) were due to system feedback failure, as depicted in Figure 4.20.

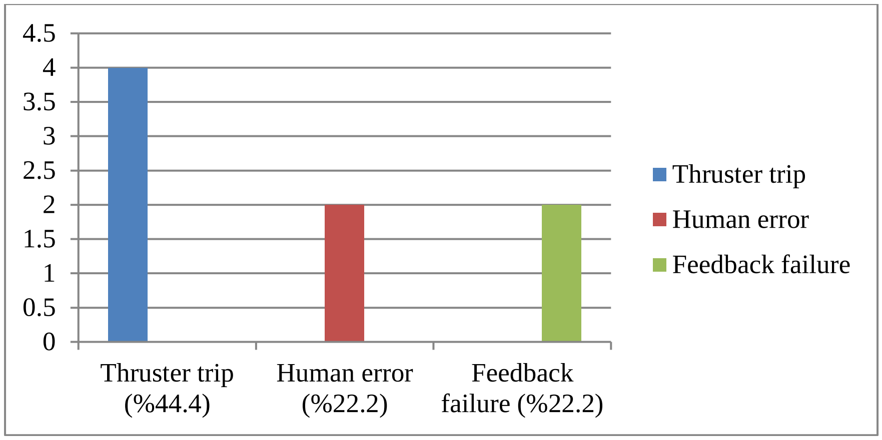

Figure 4.20 : Trigger factors for thruster/propulsion-related drift-off incidents.

In addition to the aforementioned considerations, it is noteworthy that during ROV operations, all four drift-off incidents that caused by the computer are mostly triggered by software failures, including bugs or system failures. Moreover, out of eight drift-off incidents related to PRS (main cause), it is remarkable that four of them were triggered due to issues pertaining to the degradation of the DGNSS.

4.4.1.3 Pipelay and cablelay operations

Among the 324 occurrences of drift-off incidents, 42 cases (13%) were identified as drift-off incidents that took place specifically during pipe lay and cable lay operations. Among the 42 drift-off cases examined, it was observed that 19 cases involved the use of alternative sources of PRS, while 22 cases did not use an alternative source for PRS, resulting in the lack of redundancy. Lastly, one of them was recorded as unidentified. Figure 4.21 illustrates the utilisation of PRS during pipelay/cablelay ships/operations.

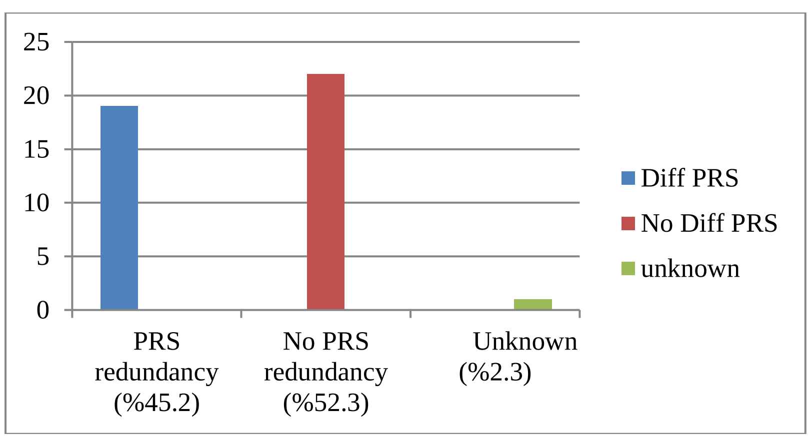

Figure 4.21 : Selection of different PRS for pipelay/cablelay ships/operations.

After conducting a thorough examination of the factors that contribute to drift-off incidents during pipe lay and cable lay operations, a comprehensive analysis of 42 drift-off cases reveals the main causes. Among these cases, the majority can be attributed to the following factors: human factor-related failures account for eight cases (19%). Similarly, PRS-related failures account for eight cases (19%), and computer-related failures account for eight cases (19%). Lastly, thruster and propulsion-related failures account for seven cases (16.6%), as seen in Figure 4.22.

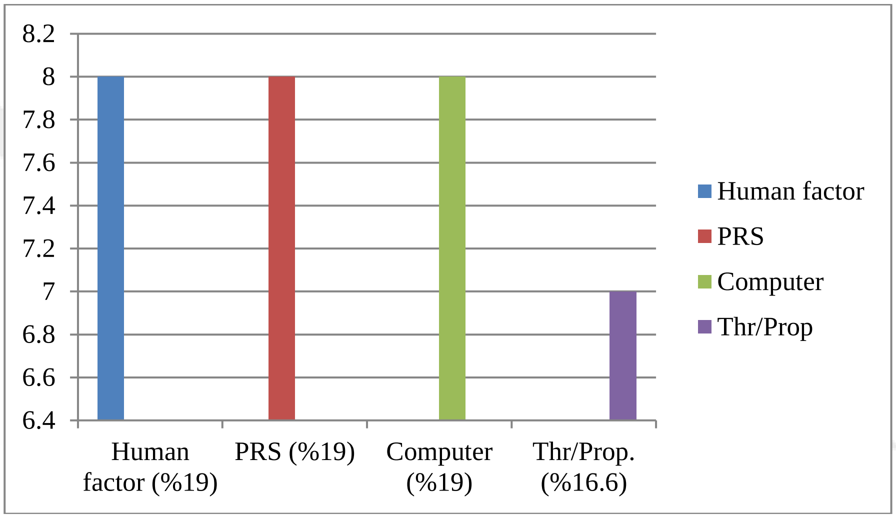

Figure 4.22 : Main causes of drift-off incidents on pipelay/cablelay ships/ops.

Upon examining solely secondary causes, the following are predominantly recorded in respective order: Out of the overall number of incidents, 17 cases (40.5%) were attributed to human factors, while five cases (11.9%) were caused by electrical failures, and two cases (4.7%) were associated with computer-related failures. The distribution of secondary causes during pipe lay and cable lay ship operations can be seen in Figure 4.23.

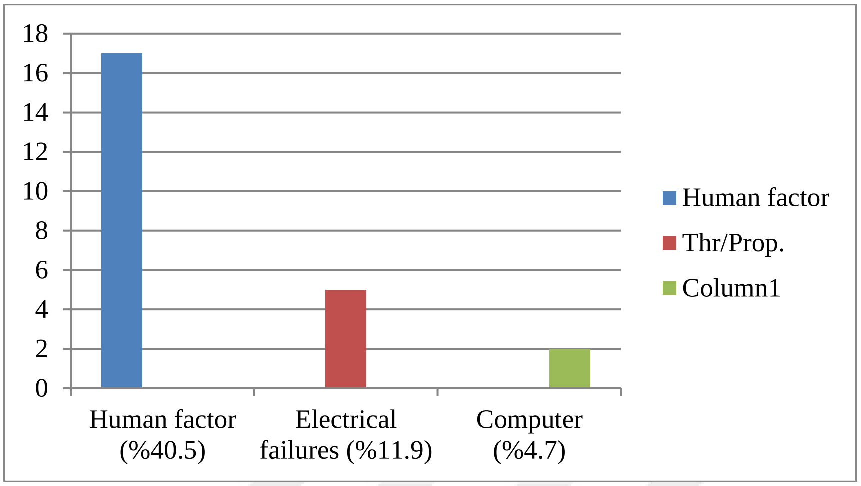

Figure 4.23 : Secondary causes of drift-off incidents on pipelay/cablelay ship/ops.

In the investigation of 20 drift-off incidents involving human factors (three of them are identified as main causes, while the remaining 17 cases attributed to secondary causes), the majority of these drift-off incidents were triggered by the following means: There were four cases are triggered by (20%) incorrect command, four cases are triggered by (20%) lack of knowledge, and three cases (15%) triggered by accidentally pressing the button. Figure 4.24 presents the distribution of trigger factors for human-related drift-off incidents.

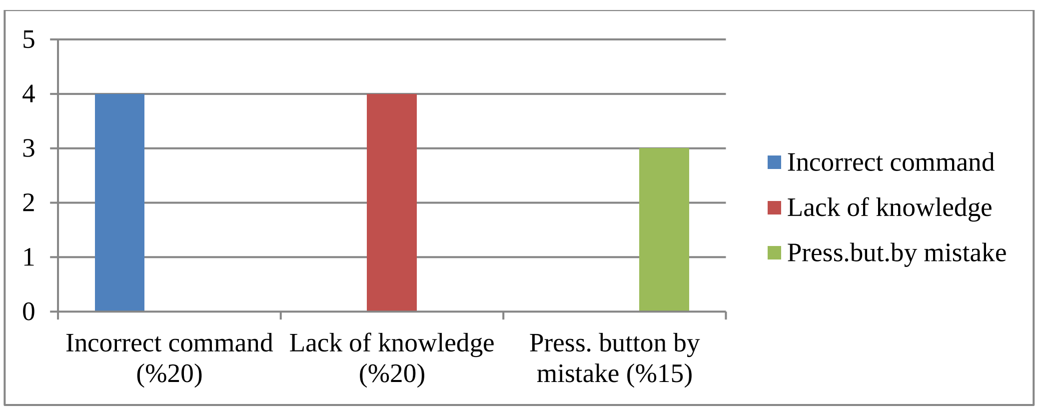

Figure 4.24 : Trigger factors for human factor-related drift-off incidents.

Additionally, it has been observed that there have been eight drift-off incidents that are related to computer failures. Out of the total of eight incidents, a majority of six (75%) are triggered by software failures. One incident (16.6%) is triggered by UPS failure, while another incident (16.6%) is associated with the human factor that is considered and analysed under the human factor category.

Besides it has been observed that there have been eight drift-off incidents pertaining to PRS failures (detected as the main cause). Out of the overall these incidents, a majority of five are triggered by (62.5%) the degradation of DGNSS.

4.4.1.4 Diving

Among the 324 occurrences of drift-off incidents, 41 cases (12.6%) were identified as drift-off incidents that took place specifically during diving operations. Among the 41 drift-off cases examined, it was observed that 39 cases involved the use of alternative sources of PRS, while one case did not use an alternative source for PRS, resulting in the lack of redundancy. Lastly, one of them was recorded as unidentified. Similar to drilling operations, a significant proportion of diving vessels (95%) employed an alternative PRS source and possessed sufficient redundancy, as seen in Figure 4.25.

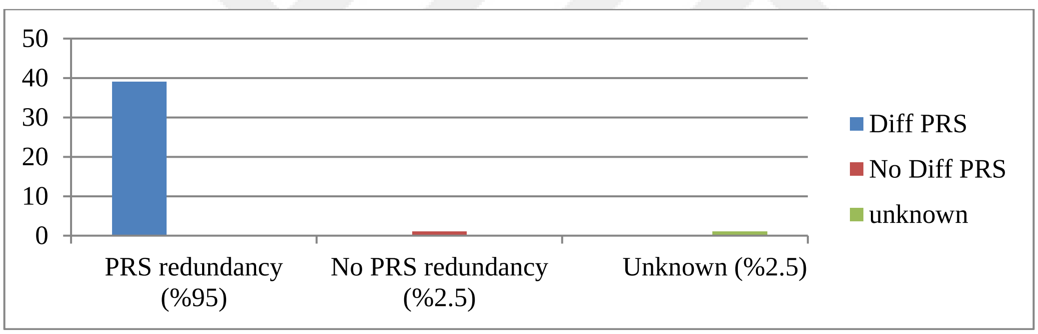

Figure 4.25 : Selection of different PRS for diving ships/operations.

Figure 4.26 presents the main factors that contribute drift-off incidents occurring during diving operations. Among the 41 drift-off cases, the main causes are primarily: 12 cases (29.2%) were attributed to failures associated with human factors, while 10 cases (24.4%) were linked to failures connected to environmental factors. Additionally, six cases (14.6%) were caused by power-related failures, and six cases (14.6%) were attributed to thruster/propulsion-related failures.

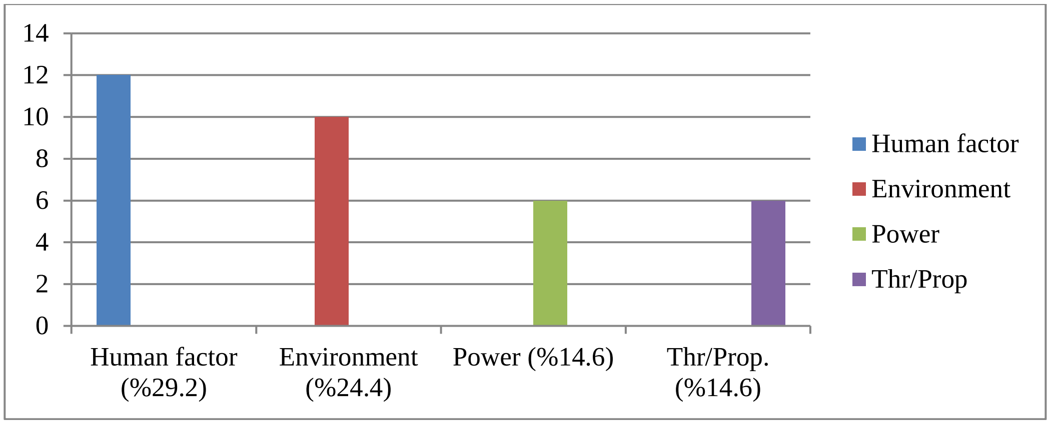

Figure 4.26 : Main causes of drift-off incidents on diving ships/operations.

Figure 4.27 displays the secondary causes exclusively, with the majority being categorised as follows: 11 cases (26.8%) attributed to human factors, eight cases (19.5%) attributed to environmental factors, five cases (12.2%) attributed to thruster and propulsion failures, three cases (7.3%) attributed to poor procedures, and three cases (7.3%) attributed to computer-related problems.

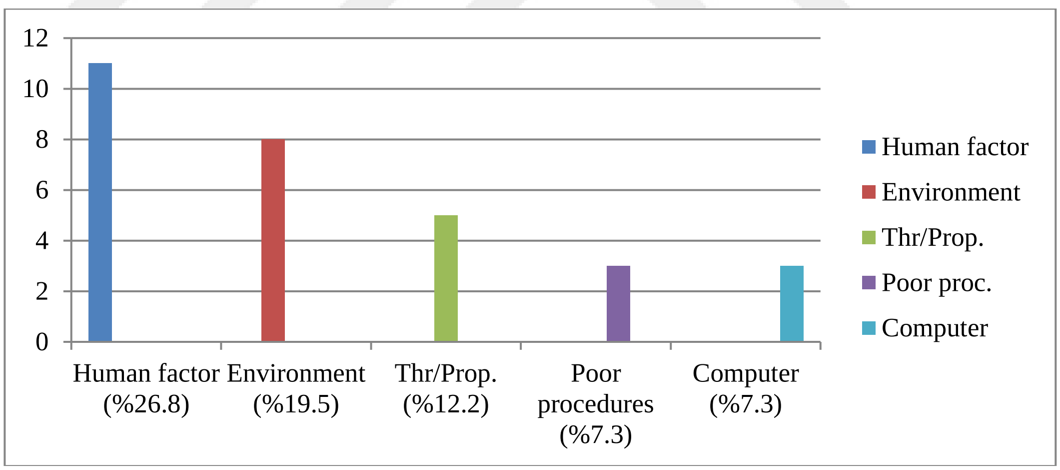

Figure 4.27 : Secondary causes of drift-off incidents on diving ships/operations.

Upon conducting an investigation into the loss of position incidents involving drift-off cases, which are associated with human factors, it is observed that 12 cases (29.2%) can be attributed to the human factor as the main cause. Out of the total of 12 incidents examined, nine cases (75%) also exhibited human error influences as the secondary cause. It is widely acknowledged that in cases when the main cause of an incident is attributed to human-related errors, the secondary cause or root cause is likewise closely linked to human errors.

Out of 12 drift-off incidents observed, a majority of nine cases (75%) were found to be triggered by either accidentally pressing the button or pressing the standby button.

When considering drift-off incidents that are associated with the environment, it is seen that 10 cases (24.4%) are attributed to environmental failures. Moreover, a significant majority of cases, namely seven out of ten (70%), demonstrate environmental factors as a secondary cause. It is widely acknowledged that in cases when the main cause of an incident is attributed to environmental factors, the secondary cause or root cause is likewise associated with the environment. Besides, the trigger factors can be identified as squalls, swells, currents or sudden changes, and waves.

The investigation of power-related drift-off incidents encompasses a total of six drift-off incidents. Among these, two cases were attributed to human factors (as the secondary cause), while the remaining four cases were attributed to power blackouts (as the secondary cause). The power-related incidents mostly triggered by (two cases) AVR failure, (one case) fuel system failure, and (one case) generator failure.

The investigation of drift-off incidents related to thruster and propulsion failures encompasses a total of seven drift-off incidents. Among these, five cases were attributed to thruster-related failures (as the secondary cause), while one case were attributed to electrical failure (as the secondary cause), and one case were attributed to human-related failure (as the secondary cause). Five drift-off incidents (71.4%) out of seven were triggered mostly by feedback failure, as seen in Figure 4.28. The aforementioned rate is thought to be higher than normal, justifying a careful consideration in the incidents pertaining to thruster and propulsion, particularly those involving drift-off cases.

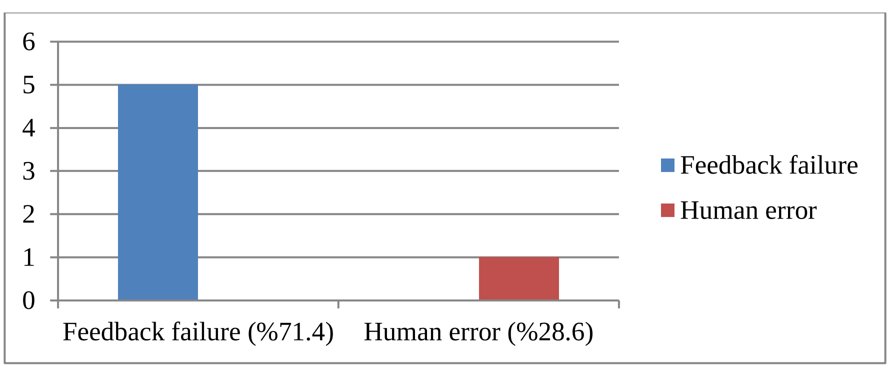

Figure 4.28 : Trigger factors for thruster propulsion-related drift-off incidents.

4.4.1.5 Cargo operations (PSV)

Among the 324 occurrences of drift-off incidents, 35 cases (10.8%) were identified as drift-off incidents that took place specifically during offshore cargo operations. Out of 35 drift-off cases, it was observed that 17 cases involved the use of alternative sources of PRS, while 17 cases did not use an alternative source for PRS, resulting in the lack of redundancy. Lastly, one of them was recorded as unidentified. Figure 4.29 illustrates the main factors that contribute the occurrence of drift-off incidents during cargo operations.

The main causes are mostly outlined as follows: A total of nine cases (25.7%) were attributed to PRS-related failures, while nine cases (25.7%) were attributed to failures related to thruster and propulsion. Additionally, eight cases (22.8%) were attributed to failures related to human factors.

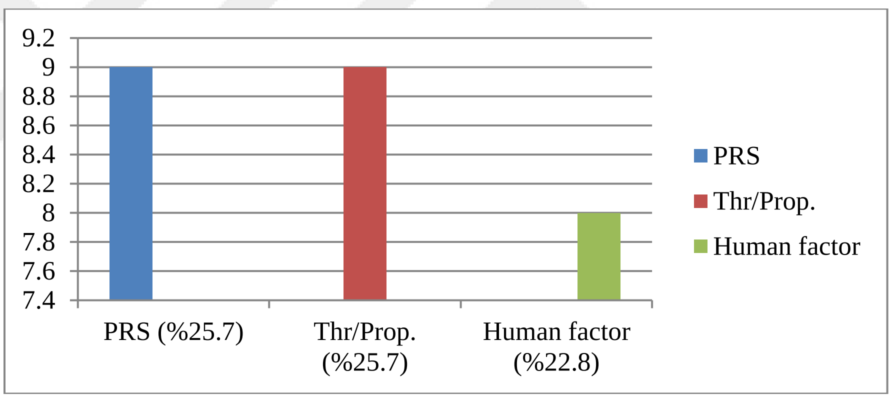

Figure 4.29 : Main causes of drift-off incidents on cargo ships/operations.

Upon examining solely secondary causes, the following are predominantly listed in respective order: Out of the total number of incidents examined, 10 cases (28.5%) were attributed to human factors, five cases (14.2%) were caused by PRS, four cases (11.4%) were a result of thruster/propulsion-related failures, and additional four cases (11.4%) were attributed to computer failures, as visually illustrated in Figure 4.30.

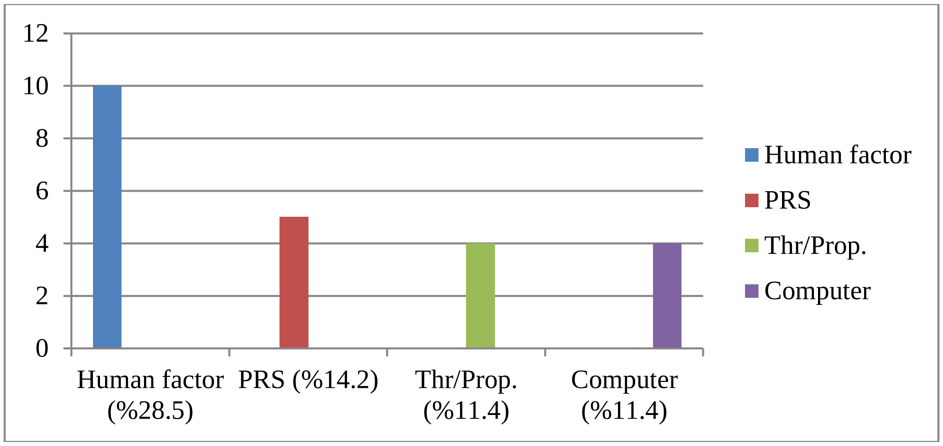

Figure 4.30 : Secondary causes of drift-off incidents on cargo ships/operations.

Based on the findings, a total of 15 drift-off incidents were identified, related to human factors (specifically, five of them as the main cause, while 10 cases as secondary causes). Out of a total of 15 drift-off incidents, six cases (40%) were triggered by accidentally pressing the button or pressing the standby button. Additionally, three cases (20%) were triggered by lack of knowledge, and three cases (20%) were triggered by an incorrect command or incorrect mode, as visually shown in Figure 4.31.

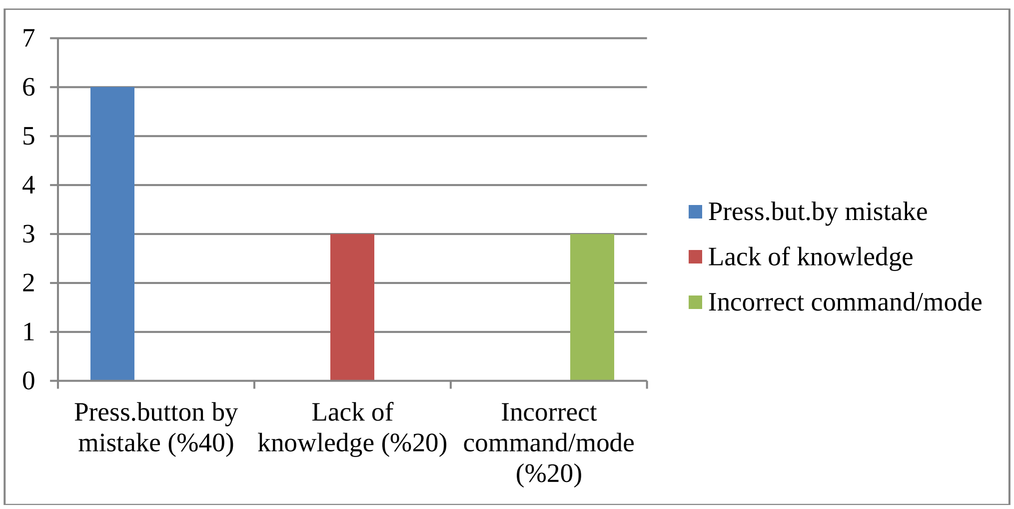

Figure 4.31 : Trigger factors for human factor related drift-off incidents.

4.4.1.6 W2W, Gangway, Passenger operations

During the operation W2W activities, namely gangway operations involving the transfer of personnel, a total of 17 drift-off incidents were recorded, accounting for 5.2% of the overall occurrences. It has been noticed that all DP vessels that were engaged in drift-off incidents utilised various alternative sources of position reference systems.

Upon investigating the factors contributing drift-off incidents during W2S operations, it was observed that out of a total 17 drift-off cases, the main causes can be briefly stated as follows: There were five cases (29.4%) attributed to human-related failures, four cases (23.5%) attributed to PRS-related failures, and three cases (17.6%) attributed to thruster propulsion-related failures.

Upon examining solely triggering factors, it was observed that three drift-off incidents attributed to a lack of knowledge, one case was linked to an incorrect mode selection, and another one was a result of accidentally pressing the button. Also, there are three drift-off incidents have been seen as a result of swells or waves being exposed to the beam of the vessel. Consequently, it is crucial to avoid being affected by lateral wind, swell, and waves while conducting DP operations. As seen in the capability plot depicted in Figure 1.7, the vessel exhibits a higher level of positioning stability when exposed to winds or waves originating from the bow direction compared to those originating from the athwart-ship direction.

4.4.1.7 FPSO and shuttle tankers (offshore load/offtake)

Among the 324 occurrences of drift-off incidents, 15 cases (4.6%) were identified as drift-off incidents that took place specifically during offshore load/off take operations conducted by FPSO vessels or shuttle tankers. It is has been observed that a limited number of incidents utilised alternative sources of PRS, observed in only six cases.

Moreover, the main causes are mostly categorised as follows: six cases (40%) were attributed to failures related to PRS, four cases (26.6%) were attributed to power-related failures, and two cases (13.3%) were attributed to human-related failures.

Upon examination of secondary causes during FPSO and Shuttle tanker operations, it may be simply stated as follows: four cases (26.6%) were attributed to human-related failures, whereas three cases (20%) were attributed to sensor problems, namely unreliable sensors.

When examining the trigger factors alone, the four drift-off incidents caused by human-related failures have trigger factors such as: two cases (50%) were attributed to accidentally pressing the button or pressing the stand-by button, while one case (25%) was attributed to a lack of knowledge. Last but not least, it is noteworthy that five drift-off incidents out of six cases (83.3%) related to PRS problems are triggered by interference problems.

4.4.2 Drive-off incidents

In the examination of drive-off incidents, a total of 61 drive-off (LoP) incidents were observed. Out of 61 drive-off cases, it has been noted that 17 incidents occurred in the absence of an alternative source of PRS. Conversely, 40 cases were observed on vessels utilised alternative sources for PRS, hence providing redundancy. Figure 4.32 shows the distribution of drive-off incidents that occurred during different offshore operations. To summarise, the analysis reveals that 19 cases with cargo operations (31.1%), nine cases with diving operations (14.7%), seven cases with pipelay/cablelay operations (11.4%), seven cases with ROV operations (11.4%), and five cases with drilling operations (8.2%). Collectively, these five categories encompassed 76.8% of the total drive-off (LoP) incidents, surpassing the halfway mark.

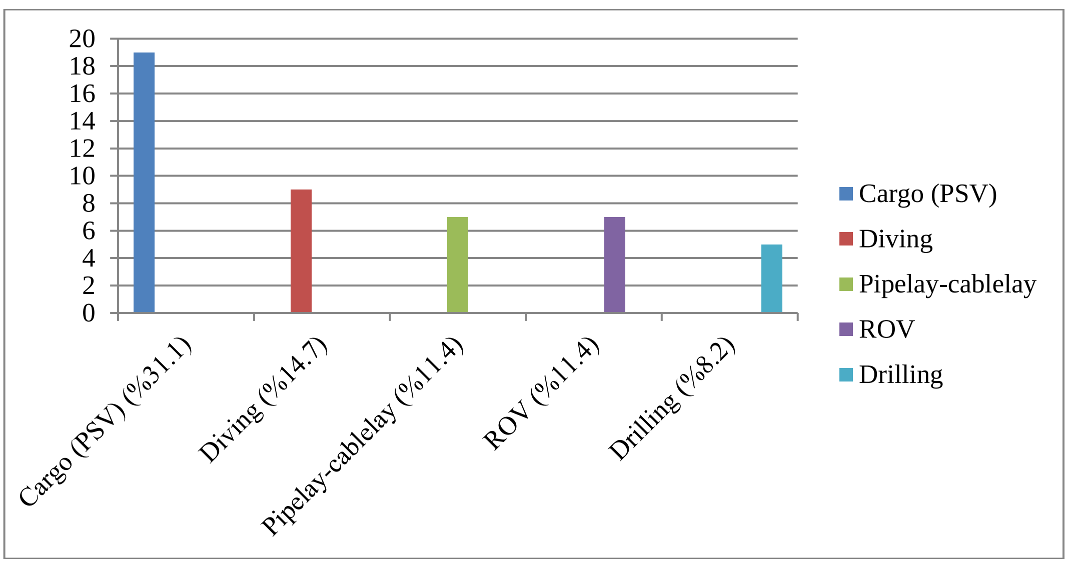

Figure 4.32 : Distribution of drive-off incidents as per operations.

4.4.2.1 Cargo operations (PSV)

Among the 61 drive-off incidents, there are a total of 19 cases (31.1%) that took place during cargo (PSV) operations. Out of 19 drive-off cases, it was observed that 10 cases utilised alternative sources of PRS, while nine of them did not utilise alternative various sources for PRS and therefore did not have any redundancy.

Upon conducting examination into the main factors contributing drive-off incidents during cargo operations, the main causes can be stated as follows: According to the data shown in Figure 4.33, 10 cases (52.6%) were attributed to thruster and propulsion failures. Additionally, five cases (26.3%) were reported to the failures related to PRS, while three cases (15.7%) were attributed to human factors.

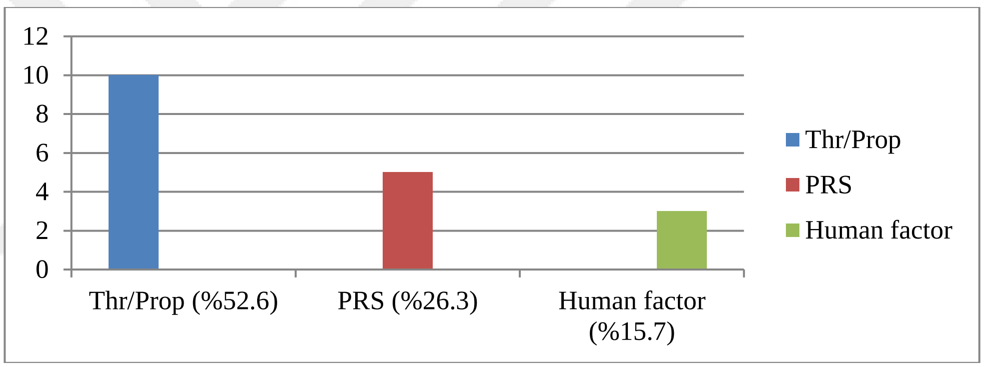

Figure 4.33 : Main causes of drive-off incidents during cargo (PSV) operations.

Upon examining solely secondary causes: five cases (26.3%) were attributed to PRS, four cases (21%) were attributed to human error. Similarly, four cases (21%) were attributed to thruster and propulsion failures, as seen in Figure 4.34. However, it is observed that human factors and PRS factors have been associated with each other for these drive-off incidents.

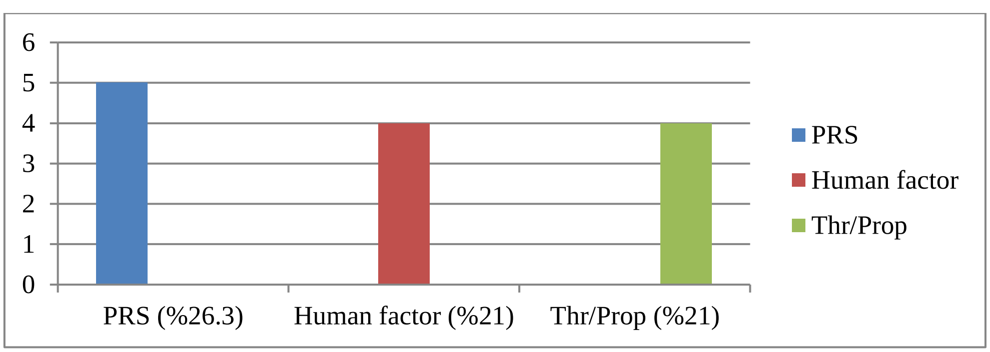

Figure 4.34 : Secondary causes of drive-off incidents during (PSV) operations.

4.4.2.2 Diving operations

Among the 61 drive-off incidents, there are a total of nine cases (14.7%) that took place during diving operations. Various alternative sources for PRS were utilised in all of the cases, hence ensuring redundancy. Looking into the main factors causing drive-off incidents during diving operations, the main causes can be stated as follows: five cases (55.5%) were attributed to thruster and propulsion reasons, three cases (33.3%) were attributed to PRS-related failures and one case (11.1%) were attributed to computer failure.

4.4.2.3 Pipe lay and cable lay operations

Among the 61 drive-off incidents, there are a total of seven cases (11.4%) that that took place during pipe lay and cable lay operations. Out of seven, only in three cases, alternative sources PRS were utilised, while in four cases, alternative sources of PRS were not employed. Looking into the main factors causing drive-off incidents during pipelay/cablelay operations, the main causes can be stated as: four cases (57.1%) were attributed to human factor or error, and three cases (42.9%) were attributed to the failures related to PRS.

Regarding the human-related trigger causes, they can be listed as follows: two cases were caused by a lack of knowledge, one case was caused by accidentally pressing the button, and one case was a result of communication failure.

4.4.2.4 ROV operations

Among the 61 drive-off incidents, there are a total of seven drive-off incidents (11.4%) that took place during ROV operations. In four cases, alternative sources of PRS were utilised, hence ensuring redundancy. Looking into the main factors causing drive-off incidents during ROV operations, the main causes can be stated as: two cases were caused due to thruster/propulsion-related failures, two cases were attributed to unreliable sensors (wind sensor failure), and two cases were caused by computers. Lastly, one case was a result of failure related to PRS.

4.4.2.5 Drilling

Among the 61 drive-off incidents, there are a total of five drive-off incidents (8.2%) that took place during drilling operations. In all of the drive-off incidents (100%), alternative sources of PRS were utilised. Upon investigating the main factors causing drive-off incidents during drilling operations, the main causes can be stated as: three cases were attributed to thruster/propulsion-related failures and two cases were attributed to PRS-related failures. Moreover, thruster failure causes are triggered by feedback failure and control system failure, whereas PRS-related causes are triggered by the degradation of DGNSS and software failures (bug).

5. CONCLUSION AND RECOMMENDATIONS

The application of association rules analysis to DP incident data allows for both quantitative analyses of single factors contributing to incidents and their attributes, as well as the exploration of mining associations among multiple factors. This process presents a challenge for traditional mathematical analysis methods. The results reveal that the main causes of DP incidents are mostly attributed to thruster and propulsion failures. On the other hand, secondary or trigger causes that initiate the main causes are predominantly associated with human factors and electrical-related failures. The following outcomes and findings may be provided based on the study of the learned strong association rules:

(i) Based on the analyses of incident consequences, it is obvious that the human factor plays a significant role in the occurrences related to DP incidents, particularly those involving loss of position and drift-off incidents.

(ii) If the secondary cause is attributed to human error, it results in a significant consequence of 88% drift-off incidents.

(iii) In the event when human error is identified as the main cause, it can be observed that there is consequence of 87% drift-off incidents.

(iv) It is a well-established fact that environmental conditions consistently lead to a 100% occurrence of drift-off incidents.

(v) If the power-related failures are the main cause, the resulting consequence is a 100% occurrence of drift-off incidents.

(vi) If the main cause is related to the thruster or propulsion systems, the resulting consequence is a significant proportion 65% of drift-off incidents.

(vii) Among all categories, drill ships and their operations are the most prevalent category in which drift-off incidents incidents occur, accounting for 20% of such occurrences.

(viii) During drilling operations, it has been shown that 90% of these incidents that occur are associated with drift-off cases.

(ix) During diving operations, it has been shown that 82% of these incidents that occur are associated with drift-off cases.

(x) The majority of the drive-off incidents, namely 31.1%, took place during cargo operations onboard PSVs.

(xi) Utilising alternative and various sources of PRS offers redundancy, although it does not exclusively guarantee the prevention of LoP incidents.

(xii) If the antecedent failure is attributed to PRS, the resulting consequence is and occurrence of drive-off incidents at a rate of 85%.

5.1 The Most Frequent Main Causes

The results reveal that the most significant main causes of DP incidents can be listed as follows: thrusters/propulsion (24%), computers (15%), power (14%), PRS (13%), and human factor-related failures (9%) as seen in Table 5.1. These incidents entirely constitute 75% of all analysed DP incidents. Furthermore, it is worth noting that thruster and propulsion training is a crucial aspect of competency for dynamic positioning key personnel. Furthermore, it is imperative for DP key personnel to possess adequate knowledge and expertise in DP computer use, power management, and position reference systems while working onboard.

Table 5.1 : Most frequent main causes of DP incidents (2004–2021).

Main causes	Number	%
Thrusters/propulsion	320	24%
Computer	199	15%
Power	191	14%
PRS	182	13%
Human factor	120	9%
Total	1012	75%

5.2 The Most Frequent Secondary Causes

The findings indicate that human factors, when considered as a secondary cause, account for 54.5% of the occurrences, whereas electrical problems contribute to 13.5% of the DP incidents within the period of five years (2017–2021).

When examining both DP incidents and DP undesired events in the same analysis, it is observed that the human factor (as a secondary cause) is responsible for 30.6% of these incidents, while electrical problems account for 33.2% of the incidents, as indicated in Table 5.2. It is revealed that the human factor remains a significant influence in the occurrence of DP occurrences. Besides, electrical failures are the second significant contributing factor for DP incidents.

Table 5.2 : Most frequent secondary causes of DP incidents (2017–2021).

Secondary causes (DP incidents)	Number	%
Human factor	73	54.5%
Electrical	18	13.5%
Total	91	68%
Secondary causes (DP incidents & undesired events)	Number	%
Human factor	131	30.6%
Electrical	142	33.2%
Total	273	63.8%

5.3 The Most Frequent Trigger Factors

A comprehensive analysis of 38 DP incidents has been documented based on the dataset established at the beginning of the study. The occurrence of these incidents may be attributed to the human factor, which acts as the underlying cause for both main and secondary factors, as seen in Figure 5.1.

Main_Cause	Secondary_Cause	Trigger(Dueto)	Incident_Type	Driftoff-Driveof	Different_PRS_Sources_Onli	OpsStatus
HumanFactor	HumanFactor	PressingButtonbyMistake	LoPos	Driftoff	Yes	GangwayOps
HumanFactor	HumanFactor	CommunicationFailure	LoPos	Driftoff	No	Pipelay
HumanFactor	HumanFactor	PressingButtonbyMistake	LoRed	Driveoff	Yes	Drilling
HumanFactor	HumanFactor	PressingButtonbyMistake	LoPos	Driveoff	unknown	Offsh-Load-Offtake
HumanFactor	HumanFactor	PressingButtonbyMistake	LoPos	Driveoff	No	Pipelay
HumanFactor	HumanFactor	LackofKnowledge	LoPos	Driftoff	Yes	Survey
HumanFactor	HumanFactor	PressingButtonbyMistake	LoPos	Driftoff	No	Cargo
HumanFactor	HumanFactor	PressingButtonbyMistake	LoPos	Driftoff	Yes	Diving
HumanFactor	HumanFactor	PressingButtonbyMistake	LoRed	No	Yes	Diving

Figure 5.1 : Human factor (both as main and secondary cause).

Out of 38 DP incidents, 21 incidents (55.2%) were attributed to accidentally pressing the button, and 5 incidents (13.1%) were attributed to pressing the wrong or standby button. Table 5.3 illustrates the visual representation of trigger (initiating) factors along with accompanying comments that should be taken into account.

Table 5.3 : Most frequent trigger (initiating) factors (2004–2021).

Trigger (initiating)	No of incident	(%)	Comments
Accidentally pressing the button	21	55.2%	personal awareness
Pressing the wrong or standby button	5	13.1%	personal awareness, experience, knowledge
Total	26 (out of 38)	68.3%	

It is observed that accidentally pressing the button or pressing the wrong button are the most probable reasons that trigger or initiate DP incidents. Furthermore, a total of 120 DP incidents were recorded, whereby human factors were identified only as a secondary cause, and thereafter, their trigger (initiating) factors are presented in Figure 5.2.

Main_Cause	Secondary_Cause	Trigger(Dueto)	Incident_Type	Driftoff-Driveof	Different_PRS_Sources_Onli	OpsStatus
PRS	HumanFactor	LackofKnowledge	LoPos	Driftoff	Yes	Offsh-Load-Offtake
Computer	HumanFactor	LackofKnowledge	LoPos	Driftoff	Yes	Pipelay
HumanFactor	HumanFactor	LackofKnowledge	LoPos	Driftoff	Yes	Survey
PRS	HumanFactor	LackofKnowledge	LoPos	Driveoff	Yes	Diving
Environment	HumanFactor	LackofKnowledge	LoPos	Driftoff	Yes	Drilling
HumanFactor	HumanFactor	LackofKnowledge	LoPos	Driftoff	unknown	PaxTransfer
HumanFactor	HumanFactor	LackofKnowledge	LoPos	Driftoff	No	ROV
PRS	HumanFactor	LackofKnowledge	LoPos	Driftoff	Yes	Cargo

Figure 5.2 : Human factor (only as secondary cause).

Table 5.4 displays a comprehensive list of the most human-related trigger factors that initiate secondary or main causes of DP incidents that occurred from 2004 to 2021. Accidentally pressing the button is the first probable factor that triggers DP incidents, with a percentage of 26.6%. Furthermore, the lack of knowledge of DP personnel is the second significant factor, initiating DP incidents. Other trigger factors are recorded as degradation of DGNSS, incorrect command, current or sudden change, and pressing the wrong or standby button respectively.

Table 5.4 : Most frequent trigger (initiating) factors (2004–2021).

Trigger (initiating)	No of incident	(%)	Comments
Accidentally pressing the button	32	26.6%	personal awareness
Lack of knowledge	18	15%	personal experience, knowledge
DGNSS degraded	9	7.5%	experience, knowledge
Incorrect command	8	6.6%	experience, knowledge
Current/Sudden change	6	5%	environmental, experience, knowledge
Pressing the wrong or standby button	5	4.1%	personal awareness, experience, knowledge
Total	78 (out of 120)	65%	

Additionally, Figure 5.3 presents a concise overview of potential generic antecedents and consequences associated with human factors and variables.

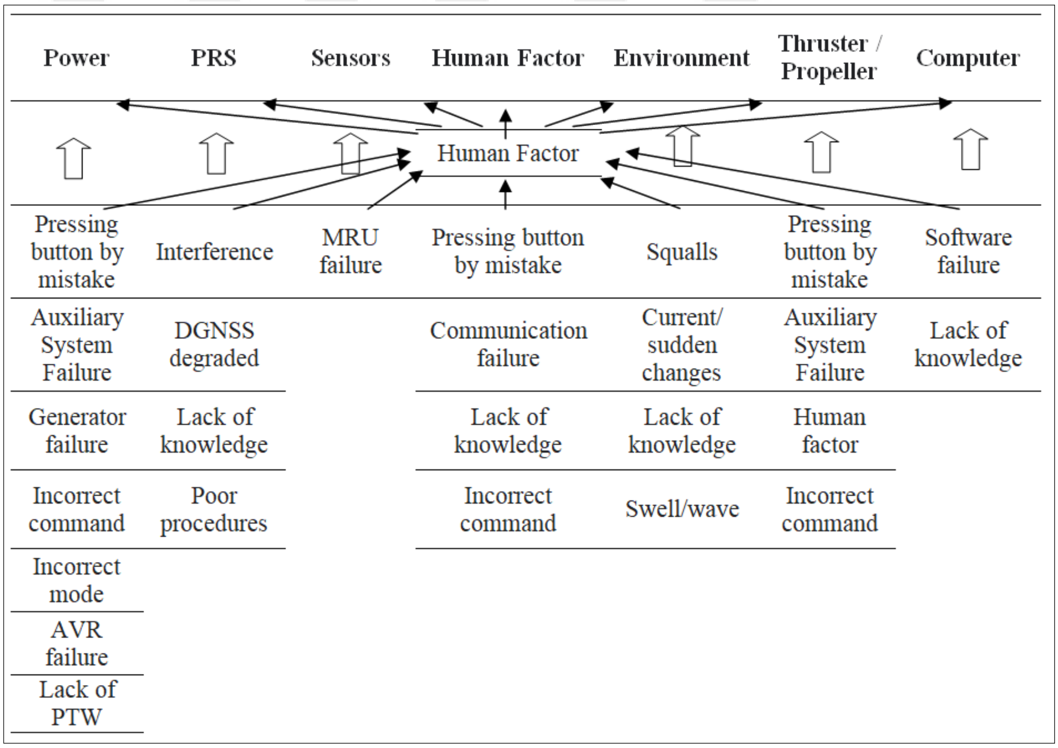

Figure 5.3 : Possible antecedents and consequences for human factor.

5.4 Recommendations

The aforementioned findings indicate that the human element continues to exert a significant impact on dynamic positioning incidents, particularly as a triggering factor. It is also strongly thought that not only theoretical knowledge but also practical experience level is significant to minimise the risks of DP incidents. This section outlines the conclusion of the study, followed by recommendations.

Scientific and accurate exploration of association rules between the variables of incident causation and the attributes of incidents is feasible. Prevention measures are proposed based on the examination of robust association rules pertaining to DP incidents. The results of this doctorate thesis address a notable gap in the existing literature, providing the most recent and up-to-date DP incident records spanning from 2004 to 2021. Furthermore, the findings of this study hold practical implications for key personnel employed on DP vessels, ship managers overseeing DP vessel operations, and relevant regulatory bodies. These results contribute to a deeper understanding of the many elements that influence DP accidents, thereby enhancing awareness among these stakeholders.

Taking into account the results provided above, this Ph.D. thesis aims to propose a framework for various trainings and provide the following recommendations for:

- The Nautical Institute,
- International Maritime Contractors' Association (IMCA)
- Dynamic Positioning Committee (DPC)
- DP vessel managers and operators
- Clients in the offshore oil and gas industry
- Training centres

Finding-1: According to the above results, 'lack of knowledge of DP personnel' has a 15% chance of triggering DP incidents. Moreover, incidents initiated by 'DGNSS degradation' are 7.5%, and 'giving the incorrect command' consists of 6.6%. This is thought to be related to personal experience and a lack of knowledge.

Recommendation-1: Recognizing the significance of practical knowledge, it is recommended to increase the duration of DP simulator courses. The more time trainee DPOs spend in DP simulator, the more practical knowledge they will gain. It is thought to be cost-effective to allow DPOs to gain hands-on experience in a simulator environment, comparing real-life and simulator incidents.

Finding-2: The experience gained during practical learning is considered more effective and utilises the competence of DPOs. Based on the prevailing criteria set forth by the Nautical Institute, it is stipulated that a minimum of 60 active days of sea time is necessary subsequent to the completion of the DP simulator course (Phase 3). Additionally, DP trainees have the opportunity to transfer a maximum of 30 active DP days completed prior to the DP simulator course (following the DP induction course/Phase 1).

Recommendation-2a: The duration of required DP sea time, which consists of just two hours per day, is deemed insufficient for the completion of 60 days following the successful completion of the DP simulator course (Phase 3). As a result, policymakers are encouraged to consider extending the DP sea time duration (currently set at two hours for each DP sea time day) or extending the mandated overall sea time, which is currently set at 60 days in length. Through the implementation of this modification, prospective dynamic positioning operators (DPOs) will be afforded greater opportunities to get hands-on practical experience. (Reference rules associated with**:** 1.7, 1.8, 2.1, 2.2, 2.7, 2.11, 3.1, 3.2, 3.3, 3.4, 4.2, 4.9, 4.10, and 4.17)

Recommendation-2b: Currently, in accordance with the guidelines set out by the Nautical Institute, there exists a provision for DP trainees to transfer a maximum of 30 active DP days completed prior to the DP simulator course. It is recommended to engage in active DP days exclusively following the successful completion of the DP simulator course. It is not recommended to transfer any surplus active sea time days acquired prior to the DP simulator course (Phase 3) to subsequent phases, such as Phase-4. (Reference rules associated with: 1.7, 1.8, 2.1, 2.2, 2.7, 2.11, 3.1, 3.2, 3.3, 3.4, 4.2, 4.9, 4.10, and 4.17) Therefore, this finding may be considered a promising aspect of this study.

Finding-3: According to the strong association rules, environmental factors always result in LoP drift-off incidents.

Recommendation-3: Meteorology training combined with DP operations, such as actions to take during emergencies or under different extreme weather conditions (squalls, solitons, currents, etc.), is recommended to provide for all DPOs. Besides, maintaining continuous and vigilant watchkeeping is of significant importance for ensuring the safety of operations. (Reference rules associated with: 1.5, 2.1, 3.3, 3.4, 3.5, 3.6, 4.1, and 4.5)

Finding-4: Results reveal that the most main causes of DP incidents are thrusters/propulsion-related failures (24%), computer-related failures (15%), power-related failures (14%), PRS failures (13%), and human factor-related failures (9%), as seen in Table 5.1. Considering the significant impact of power-related failures, blackout recovery training is highlighted as crucial.

Recommendation-4: All DPOs, EROs as well as ETOs, should be well-versed in black out recovery process and supposed to know their vessel's specific characteristics. (Reference rules associated with: 5.3)

It is recommended to provide comprehensive training for DP key personnel (DPOs, EROs, and ETOs) before they embark on their vessel assignment. This training should encompass ship-specific thruster/propulsion training, as well as power management training, covering the concept of different propulsion systems, their limitations, blackout prevention and recovery processes. (Reference rules associated with: 5.3)

Finding-5: According to the results of this study, it was found that pressing the wrong button by mistake is the major cause that triggers or initiates DP incidents, with a percentage of 55.2.

Recommendation-5: It is recommended to perform a more detailed analysis regarding the human factor and situational awareness to increase awareness and minimise the risks of DP incidents for future research. The limitations of this study do not allow the researchers to perform a detailed analysis of human situational awareness, which may contribute to mistakes in DP incidents.

Finding-6: The results of this study prove that the number of DP incidents has still been increasing. It is known that after completing the NI training and certification process, a DPO can start working solely as a responsible DP watchkeeping officer.

Recommendation-6: It is highly recommended that DPOs also undertake a specific course on how to act during DP emergencies. This is simulator-based training called DP Emergency Situations**,** allowing operators to learn how to react in the following situations.

- What actions should be taken in the event of losing all wind sensors?
- What actions should be taken in the event of losing all gyro compasses?
- What actions should be taken in the event of losing one or more PRS?
- What actions should be taken in the event of blackout?
- What actions to should be taken in the event of LoR?
- What actions should be taken in the event of (LoP) drift-off?
- What actions should be taken in the event of (LoP) drive-off?
- What actions should be taken in the event of a sudden environmental change, such as a change in sea current, wind speed, gusts, squalls, solitons, etc.?

Finding-7: The type of ship or operation involved in DP incidents can be listed as diving ships (17.3%), drill ships (16.4%), ROV vessels (14.6%), and PSV/cargo (12.5%). Also, the DP equipment class onboard construction vessel, pipe lay vessel, and drill ship is mostly DP-3, while the other DP vessels are installed with DP-2 or DP-1. It is understood that DP experience gained onboard a supply vessel and a drill ship is not the same in terms of content and the amount of DP hours practiced. Although the DP system and principles are mainly similar, the content of different types of offshore vessels and their operations may differ from each other and require additional skills and experience from DPOs.

Recommendation-7: It is recommended that an expert specialisation programme be developed for the industry. To give an example, a DPO who has experience onboard a DP-3 drill ship for a minimum of 90 DP sea time days can have a specialised certificate enabling the one to work onboard a specific offshore vessel. Unless a DPO has a specialised certificate for that type of DP vessel, s/he can be employed as a trainee DPO until s/he gains specific knowledge and experience.

Furthermore, DP vessel managers and operators should implement ship specific familiarisation training for DP key personnel who are engaged in DP operations (DPOs, EROs, and ETOs). This training module can be called home training and it should be provided either at home or in the office before embarking on the vessel.

For instance, drillship-specific training for DP key personnel should be conducted prior to boarding the vessel, focusing on the specific knowledge of its DP models, equipment types, and other related components.

In accordance with the home-training module, every DP key personnel is required to review ship-specific significant documents, a task that can be completed either at home or in the office before embarking on the vessel. These documents include, but are not limited to, the latest FMEA and DP annual trial reports, the DP operation manual, DP incident or failure reports (if any), the most recent DP audit report, WSOG, TAM, CAMO, etc. DP personnel are required to thoroughly read and comprehend these significant documents related to the specific ship they are assigned. Strengthening the training of DPOs and improving the content and quality of training will undoubtedly increase the competence of DP key personnel, thereby reducing the likelihood of DP incidents occurring from human error.

The following recommendations are provided for DP instructors and DP training centres:

Recommendation-8: Although the requirements and training scheme for becoming a DP trainer are sufficiently explained in the DPACSS (Dynamic Positioning Accreditation and Certification Scheme Standard) by the NI, it is recommended that the qualification requirements for DP instructors be continuously updated and improved in parallel with the development of technologies and the changing perceptions of the younger generation. Not only the DP courses but also other trainings such as communication skills, problem-solving, leadership development, andragogy, and life-long learning modules can be included to assist DP trainers in continuous professional development for the future's requirements.

Furthermore, it is recommended for DP training centres to encourage DP trainers to work onboard DP vessels for at least one month each year to refresh their practical skills and follow up on recent professional developments wherever applicable.

For future studies, it is recommended that the competency factors of DPOs for various types of DP vessels be identified in more detail. Within the scope of this research, the competency factors can be attained by employing specific vessel types or incident models using advanced methodologies such as machine learning, the Bayesian network method, etc.

Last but not least, situational awareness provides individuals with the capacity to remain vigilant and make better decisions, a crucial aspect for DPOs particularly during emergency situations.

It is recommended for further studies for researchers to perform more detailed analysis regarding the human factor and situational awareness in order to increase awareness and minimise the risks of DP incidents.

Disclosure statement

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