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CAST APPLICATION: A CASE STUDY OF CAPECO MULTIPLE TANK EXPLOSION

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Keywords

Accident Analysis,
Explosion,
Safety Management,
Occupational Safety,
Major Industrial Accident.

Abstract

Although major industrial accidents caused by hazardous chemicals such as petroleum products are rare in the chemical and petroleum processing industries, they cause significant financial losses, deaths and serious environmental impacts. Even though traditional accident investigation methods work well for linear systems, an accident analysis method built on systems theory helps to analyze major industrial accidents. This study analyzes the Caribbean petroleum tank terminal explosion using Causal Analysis based on Systems Theory (CAST) method. The main purpose of this research is to examine the causes of the accident with a risk assessment based on systems theory apart from traditional methods. The Caribbean petroleum tank terminal explosion was chosen for the study because it was one of the largest tank accidents in the last 50 years. In order to prevent future accidents, it is of great importance to analyze past accidents by analyzing them with new methods. For this purpose, various data and documents related to CAPECO accidents were examined in detail within the framework of CAST methodology. The CAST analysis revealed direct and indirect causal factors related to the CAPECO accident. The lack of management standardization and operational systems were the leading direct causes for the accident. Other main reasons were identified as the absence of an independent automatic overfill prevention system, a lack of considerations on the worst-case scenario, unreliable critical equipment, and inability to detect a large overflowing vapor cloud spreading into the terminal area. The study indicates that CAST methodology can reveal many causal factors at different hierarchical levels of a system.

CAST UYGULAMASI: CAPECO ÇOKLU TANK PATLAMASI ÖRNEK ÇALIŞMA

Anahtar Kelimeler

Kaza Analizi,
Patlama,
Güvenlik Yönetimi,
İş Güvenliği,
Büyük Endüstriyel Kaza.

Öz

Petrol ürünleri gibi tehlikeli kimyasalların neden olduğu büyük endüstriyel kazalar kimya ve petrol işleme endüstrilerinde nadir görülmesine rağmen, önemli mali kayıplara, ölümlere ve ciddi çevresel etkilere neden olmaktadırlar. Geleneksel kaza inceleme yöntemleri doğrusal sistemler için iyi çalışsa da, sistemler teorisine dayanan bir kaza analiz yöntemi, büyük endüstriyel kazaların analiz edilmesinde daha etkili olmaktadır. Bu çalışma, Karayip petrol tankı terminal patlamasını sistemler teorisi yöntemine dayalı nedensel analiz (CAST) yöntemini kullanarak analiz etmektedir. Bu araştırmanın asıl amacı , kazanın nedenlerini geleneksel yöntemlerin dışında sistem teorisine dayanan bir risk değerlendirmesi ile incelemektir. Karayip petrol tankı terminal patlaması kazasının araştırma için seçilme nedeni, son 50 yıl içinde gerçekleşen en büyük tank kazalarından biri olmasıdır. Gelecekte olabilecek kazaları önlemek için geçmişte yaşanan kazaları nedenleri ile yeni metodlar ile analiz ederek incelemek büyük önem taşımaktadır. Bu amaçla, CAPECO kazası ile ilgili çeşitli veri ve belgeler CAST metodolojisi çerçevesinde detaylı incelenmiştir. CAST analizi sırasında CAPECO kazasıyla ilgili doğrudan ve dolaylı nedensel faktörler ortaya çıkarılmıştır. Yönetim standardizasyonu ve operasyonel sistemlerin eksikliği, kazanın önde gelen doğrudan nedenleri olarak belirlenmiştir. Diğer ana nedenler, bağımsız bir otomatik taşma önleme sisteminin olmaması, en kötü durum senaryosunun dikkate alınmaması, güvenilmez kritik ekipman ve taşarak terminal alanına yayılan büyük

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bir buhar bulutunun tespit edilememesi olarak belirlendi. Çalışma, CAST metodolojisinin bir sistemin farklı hiyerarşik seviyelerinde birçok nedensel faktörü ortaya çıkarabileceğini göstermektedir.

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1. Introduction

Industrial accidents caused by hazardous chemicals such as petroleum products pose a significant threat to human well-being and the environment (Casal, 2018; Jung, Woo, and Kang, 2020). Although major accidents in the chemical and petroleum processing industries are rare, they might result in substantial financial loss, fatalities and the severe environmental impacts (Jung, Woo, and Kang, 2020; Hou, et. al, 2021). For this reason, industries take precautions to prevent accidents and regulators enforce them to comply with regulatory rules (Ni, et. al, 2020). Nevertheless, several tank explosion accidents occurred in the past 30 years (Atkinson, et. al, 2017; Zhang, et. al, 2019; Jung, Woo, and Kang, 2020; Hou, et. al, 2021) resulting in deaths and injuries as well as significant damages to surroundings and environment (Marsh Report, 2018).

The concept of accident investigation has been proposed in enterprises to ensure lessons are learnt and eliminate the reoccurrence of similar accidents and reduce process-based risk (Accou and Reniers, 2019). Accident investigations help to explain the causes of an accident by using accident analysis techniques (Saleh, et. al, 2010). However, the traditional methods like event tree analysis, fault tree analysis, failure modes and effects analysis, etc. (Underwood and Waterson, 2013; Kim, Nazir and Øvergård, 2016; Gür, et. al, 2021) in accident analysis are not satisfactory to analyze the system elements' interactions. In addition to the traditional systems, there are several system approach based accident analysis models (Underwood and Waterson, 2013) like Functional Resonance Analysis Method (Hollnagel, 2014; Kaya, et. al, 2019), AcciMap (Rasmussen, 1997).

CAST provides a new causality model to analyze accidents in complex socio-technical systems (Leveson, 2012). As Leveson (2011) explained, the main purpose of accident analysis is not to find someone to blame, but to maximize what can be learned from the accident. The ultimate goal of CAST accident analysis is to learn how to avoid losses in the future. CAST aims to learn as much as possible from each accident.

In this study, Leveson's CAST model is preferred to analyze the CAPECO multiple tank explosion, since CAST assists to understand the entire accident process and further promotes generating complete recommendations for improving the overall system safety while encompasses a broader view both in engineering and operational aspect of the system. Thus, this study aims to demonstrate a CAST-based accident analysis of a catastrophic vapor cloud explosion at the Caribbean Petroleum Corporation (CAPECO) facility.

2. Literature Survey

Understanding socio-technical system accidents by systems thinking approach has a significant approach in terms of accident analysis research (Salmon et al., 2012; Stanton et al., 2012). It is necessary to examine the accidents as the result of unexpected, uncontrolled relationships between the parts that make up a system and to analyze the systems as a whole. Traditional cause-effect accident models suggest that complex system accidents are caused by equipment failures or unsafe human action (Underwood and Waterson, 2013). However, as system complexity increases, accidents occur as complex phenomena within the normal operational variability of a system (Carvalho, 2011). Therefore, as a new approach, systems thinking approach and risk assessment and accident analysis methods have been developed. Systems-Theoretic Accident Model and Processes (STAMP) is one of these methods and CAST model is derived from STAMP. STPA analysis can identify all potential scenarios that could lead to losses, and these scenarios can then be used to prevent accidents (Altabbakh, et al., 2014). CAST helps to determine the accident scenario that occurred. CAST analysis of past accidents can be used to prevent further losses (Leveson, 2019).

STAMP have been applied to water contamination accident (Leveson et al., 2003), aerospace systems (Leveson, 2004), U.S. biodefense (Laracy, 2006), aircraft accidents (Nelson, 2008), railway transportation (Ouyang et al., 2010; Underwood and Waterson, 2014), and aviation (Mogles, Padget and 2018).

CAST have been applied to various fields like Korean Sewol ferry accident (Kim, Nazir and Øvergård, 2016), Soma mine disaster in Tukey (Düzgün and Leveson, 2018) and pipeline gas explosion in Taiwan (Li, et. al, 2020) by accounting human errors, constraints, organizational factors and hierarchical control levels (Leveson, 2011).

Kim and coworkers (2016) analyzed the tragic Korean Sewol ferry Ro-Ro cruise ship accident with CAST, examining the weaknesses in the security control structure from a systemic perspective. With the STAMP-based CAST accident analysis model, he analyzed the systemic problems of the Sewol accident from a broad perspective, revealing the rationale behind the decisions that led to a large number of deaths.

Düzgün and Leveson (2018) analyzed the Soma Mine accident that occurred in 2014 due to the fire in the underground coal mine and caused the death of 301 people with CAST. Considering the complex structure of the mine and the accident, the researchers had been determined that socio-technical factors such as unstructured organization and human performance in the accident and inadequate safety culture, wrong decision making and risk perception play important role in the occurrence of the accident. In addition, inadequate system control constraints are identified at each hierarchical level of the system and suggested improvements accordingly.

Li and colleagues (2020) studied the devastating underground pipeline gas explosion in Taiwan, one of the biggest oil disasters in Chinese history, with CAST analysis. They analyzed the system hazards hierarchically and the results revealed that it systematically violated inadequate control and security restrictions.

The CAST technique has been applied in this study as it will provide an in-depth understanding of how dynamic, complex system behavior contributes to accidents. It should be stated that the case study of CAPECO multiple tank accident will supportive to show that CAST analysis is suitable for situations with a high degree of uncertainty regarding accident occurrence. The accident investigation presented in this study can also be used to prevent such major industrial accidents at different levels of the accident control hierarchy.

3. Material and Method

The aim of this study is to investigate the causes of the Caribbean petroleum tank terminal explosion accident with a risk assessment based on systems theory apart from traditional methods. Analysis of the CAPECO multiple tank explosion accident with the framework of CAST methodology will have a contribution to the literature in understanding the systems thinking approach for accident analysis. In addition to that it could be a case study to prevent future accidents in petroleum industry. Therefore, various data and documents related to CAPECO accidents were examined in detail with CAST methodology.

3.1. CAPECO facility

The CAPECO was established in 1955 as a refinery. It had started to serve as a petroleum products storage facility since 2003 (CSB, 2010). The primary operations performed at the facility were product loading and unloading. The storage capacity of the facility is 341,000 cubic meters (Doğan, Scarabella and Akman, 2020). The CAPECO facility consists of 4 main sections: an administration area, a decommissioned refinery, a tank farm, and a wastewater treatment plant. In addition, the facility had a loading dock on San Juan Bay in Puerto Rico. The most basic operation performed at the facility was product loading and unloading. The unloading times are scheduled for ships arriving in port, and CAPECO pays the penalty in case of a delay in this process. The levels of the tanks were recorded by operators every morning. Only one of the tanks (Tank 107) could receive the total amount of gasoline on a ship. For this reason, sometimes discharging was done by sharing between several tanks. Due to the storage constraints and tonnage differences for incoming vessels, operators' calculations and communication were vital between operators.

At the day of the accident, five million gallons of gasoline overflowed from the aboveground storage tank and formed a vast vapor cloud to an ignition source near the plant's wastewater treatment plant (CSB, 2010). As a result of the explosions, 17 of the 48 oil storage tanks were damaged by the fire that lasted three days (CSB, 2010). Sixty-five people were working in the facility during the incident, but no fatalities happened.

3.2. CAST

CAST derived from STAMP, is a recently developed method to analyze accident causality. The CAST involves five parts as shown in Table 1: (1) assembling basic information, (2) modelling safety control structure, (3) analyzing each component in loss, (4) identifying control structure flaws and (5) an improvement program (Leveson, 2019).

Table 1. Basic components of CAST

Components of CAST	Explanation
1. Assemble Basic Information	Accident, Hazards, Constraints, Events, Physical Loss, Questions
2. Model Safety Control Structur	Model the existing safety control structure for this type of hazard. Controls and controllers and their role in the accident
3. Analyze Each Component in Loss	Contributions to Accident, Mental Model Flaws, Context, Questions
4. Identify Control Structure Flaws	Communication, Coordination, Safety Info System, Culture, Changes & Dynamics, Economics, Environmental, Questions
5. Create Improvement Program	Recommendations, Implementation, Feedback, Follow-up

In the first part, the basic information is collected to perform the analysis. The accident is described without conclusions nor blame. Questions are generated to explain why the incident occurred. The loss and hazardous state are described. Failures and unsafe interactions leading to the hazard, missing or inadequate physical controls are analyzed. In the second part, the safety control structure for the incident is modelled. In the third part, the control structure components are examined to determine why loss prevention is not sufficient. In the fourth part, flaws in the control structure are identified as general systemic factors. In the fifth part, recommendations are provided to prevent a similar loss in the future.

In this study, the authors reviewed Caribbean Petroleum Tank Terminal Explosion and Multiple Tank Fires, Investigation Report (CSB, 2010) and ÇASGEM (Doğan, Scarabella and Akman, 2020) reports analyzing tank explosion accidents CAPECO facility by using CAST.

4. Case Study

4.1. Part 1: Basic information

On Wednesday, October 21, 2009, the cargo ship approached the port in Bayamon, Puerto Rico to deliver products. CAPECO assigned 7 people, 4 of whom were its personnel, for the evacuation process of the 43,600 m3 of gasoline. There was only one tank (tank number 107) to receive this amount of product, and that tank already contained product. The authorities then decided to distribute the product to the interconnected small tanks numbered 405, 504, 409 and 411, and to send the remaining amount to tank 107 (Doğan, Scarabella and Akman, 2020).

Figure 1. Photos of the accident site (Doğan, Scarabella and Akman, 2020).

A catastrophic explosion happened at the CAPECO facility in Bayamón, Puerto Rico, on October 23, 2009 (see Figure 1). The explosion registered 2.9 on the Richter scale, occurred during the transfer of gasoline from a ship to the tank onshore (CSB, 2010). The explosion happened after the gas created a large vapor cloud, reached an ignition source near the plant’s wastewater treatment plant. Five million gallons of gasoline overflowed from the aboveground storage tank in the incident. In addition to 530 fire-fighters, 900 security guards fought intensely for 66 hours to prevent the fire spreading to other tanks. 17 of the 48 petroleum storage tanks were damaged due to the explosion and fire (CSB, 2010). The shock pressure wave of the explosion damaged nearly 300 building around the terminal. The military facility located near CAPECO had damages over $5 million (Doğan, Scarabella and Akman, 2020). Thousands of gallons of petroleum products and fire suppression foam caused environmental pollution. After reviewing several reports, the authors identified the system hazards related to the accident: gasoline vapor cloud explosion and the exposure of employees, the public, the nearby military facility, and the ecosystem to toxic chemicals. Accordingly, safety constraints were identified as follows:
System hazard 1: Gasoline vapor cloud explosion
Safety constraints:

1. Petroleum products must be under control at all times (i.e., overflow to the environment must be prevented).
2. An independent high-level alarm system must be equipped.
3. Calculations and procedures must be standardized.

Table 2 shows the proximal events leading to the gasoline vapor cloud explosion at CAPECO facility.

Table 2. The timeline of the events in the accident (CSB, 2010)

Date	Time	Event
10/22/09	01:40	Bulk pumping began into 504, 409 and 411.
10/22/09	12:15	The employee noticed that the tank level indicator was stuck while the gasoline was transferred to tank number 504. He climbed to the top of tank 504 to visually inspect the level and found that it was below the fill level. The operator and supervisor decided to close Tank 504 early and to open the valve of the tank number 409. Thus, 26,500 liters of gasoline started to flow into the 409 tank per minute. The same employee also opened the tank 411 a little and provided a small amount of gasoline flow to the tank 411.
10/22/09	22:10	The tank operators determined that Tank 411 is full and closed tank 411 and fully opened tank 409. The tank operator estimated that 409 would be full around 1 a.m.
10/22/09	23:25-24:00	Tank 409 began to overflow. The CSB calculated that the overflow lasted approximately 26 minutes.
10/23/09	24:00	The tank operator noticed fog on the ground and the road along with tanks 504, 411, and 409, and warned the supervisor. The supervisor and the operator attempted to drive around to the other side of the fog to determine the origin of the fog.
10/23/09	00:23	Security cameras recorded an ignition in the vapor cloud at the wastewater disposal facility. Explosion occurred.

The Chemical Safety Board (CSB) team arrived at the accident area two days after the explosion. The team worked with the Puerto Rico Occupational Safety and Health Administration (PR OSHA) and the US Environmental Protection Agency (EPA). The CSB found that CAPECO had insufficient regulatory requirements in case of hazard assessment and did not take proper precautions to prevent accident. The CSB noticed that the local fire department was not ready for proper response to multiple tank fires. CSB also found deficiencies in various OSHA standards and EPA policies to protect workers and the public.

4.2. Part 2: Modelling safety control structure

Safety in CAST is considered as a control problem, and thus, a safety control structure is modelled during the analysis. The authors first modelled a very high-level control structure and, then, created a detailed one. Figure 2 shows the detailed safety control structure for the accident.

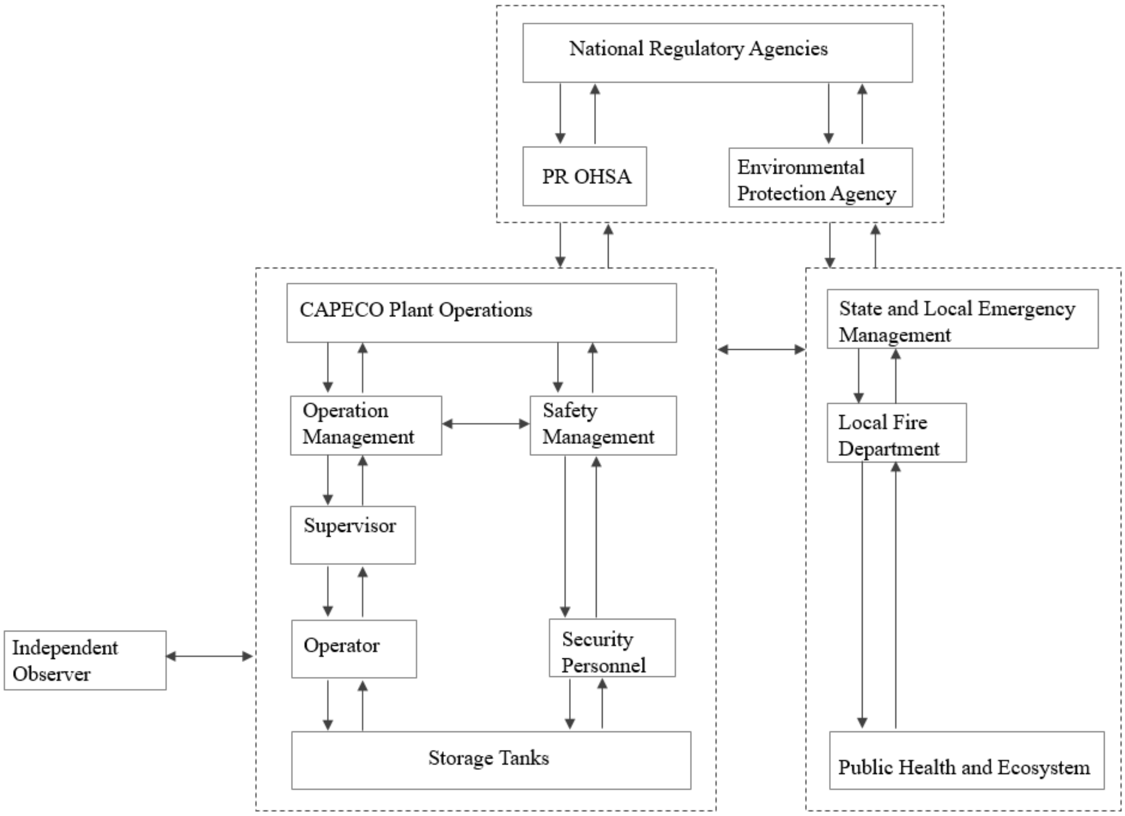

Figure 2. Safety control structure

4.2. Part 3: Analyze each component in loss

In this part, the authors analyzed each component in loss by identifying responsibilities, process model flaws and recommendations. Figure 3 shows the CAST analysis for CAPECO. In 2004, CAPECO installed transmitter cards on the float and level measuring strip that transmitted the liquid level to the computer in the operator's offices and the planning department. The computer instantly determined the liquid depth, the total volume depending on the level measuring strip, and the time-dependent flow velocities into or out of the tank and calculated the fill rate. However, during the accident day, since the computer system was not working and no data was received, the shift supervisor and the tank farm operator calculated the filling time with the data received from the planning department. Due to the frequent breakdowns of indicator devices, manual level checks and related calculations were common in CAPECO. On the evening of the incident, the level gauges of tank number 409 were not sending data to the computer. Noticing that the tank level indicator remained stuck while the gasoline was transferred to the second tank, tank number 504, the employee completely opened the corresponding tank number 409. When it was predicted that the tank number 409 would be completely filled during the shift change, the valve of the tank number 409 was almost completely closed, and the valves of the tank number 411 were opened entirely in order to avoid any overflow problems during the shift change. However, tank number 409 started to overflow and form a cloud of vapor around 24:00 before the calculated time. A fog layer formed around the tank and other tanks (Tanks 504 and 411). At 24.00 o'clock, the employee noticed a steam cloud and a sharp gasoline smell before coming near the tank. The personnel could not identify the source of the gas flowing out due to the inadequate lighting at night and the topography of the facility. The lack of sufficient lighting in the area, the use of manual lanterns prevented operators from observing whether the valves were open or closed on the night of the event. CSB detected that the safety pool drain valve for Tank 409 at the time of the incident was open when it should have been closed (CSB, 2010).

CAPECO

<u>Inadequate Control Actions:</u>
- The amount of transferred petroleum product: Only one tank can receive this amount of substance
- Level gauges of the tanks and feedback computer system not working
- The computer system and the transmitter card are not reliable
- Lack of Automatic flow restrictor or flow shut-off
- Low number of staff
- Lack of sufficient camera system in the facility
- Hourly tank level reading by the operator
- Lack of formal evacuation procedures
- Lack of preventive maintenance
- Lack of high-level alarm systems
- Poor management of terminal operations
- Organizational problems
- The internal pressure of the planning department to the operation department
- Lack of reliability of critical equipment
- Lack of reliable machine maintenance
- Lack of procedures, standards for safe working conditions
- The lack of sufficient lighting in the area

<u>Mental Model Flaws:</u>
- Inadequate risk management to prevent the accident.
- Inadequate experience and competence in risk assessment and emergency response plans.
- Inadequate emergency response

Figure 3. CAST analysis for CAPECO

The planning department's internal pressure to the operation department to obtain material income by completing the transfers in a shorter time than the anticipated in the loading/unloading operations created a risky rush in the activities. In addition, attempting to use the tanks at full capacity to obtain the maximum benefit from the tanks has become a practice by the planning department. For this reason, tanks were usually filled to the last level.

Since there is a lack of personnel and increased manual work problem in the operation department, operators generally leave the valves of the next tank open. On the day of the incident, when the operator had to change the line to fill another tank, the unit became uncontrolled due to having to call the wastewater disposal unit operator for assistance.

The operators were working with unreliable "critical equipment". It was determined that CAPECO had purchased a system with the lowest efficiency for the measurement and did not implement an adequate preventive maintenance program for its maintenance. The deficiencies in critical equipment in the level control and monitoring system (transmitters in the side indicator, float and tape level measurement system in the tank) prevented operators from determining tank levels during filling operations.

The lack of an independent warning alarm and/or an automatic flow shut-off system poses a significant risk. The security system is highly dependent on human factors, and the automation is not at the desired level is a critical security deficiency. Operators had been calculating tank levels manually for years before the accident. Therefore, instant data tracking was not possible in the control room. Manual execution of the works with personnel calculations as a result of the indifference and normalization of the administration against the improper operation of the level measurement devices increased the risk factor.

CAPECO's standard operating procedures only address activities that require a work permit and do not cover terminal operations. In 2009, guidelines on activities subject to permission, such as working with only resources and indoor work were prepared. A guide has not been established on the procedure to be followed during loading and unloading operations. There were two-page activity rules, last updated in 1999. The operation was entirely left to the experience and initiative of the operators.

Figure 4 shows the CAST analysis for the local fire department and state and local emergency management. The local fire department was not adequately equipped. This was because risk analysis was not conducted to consider and plan multiple tank fires leading to vapor cloud explosion. On the day of the incident, neither CAPECO nor the regional fire brigade has the capability to deal with a multi-tank fire of this size. To control a fire of this size, large amounts of foam had to be delivered to the top of the tanks, but there was not enough pressurization. CAPECO staff and local fire-fighters, on the other hand, were not trained for 11 tank fires caused by the vapor cloud explosion. According to an emergency plan, the worst-case scenario was explained by the burning of a single tank. Local fire brigades did not have enough training and resources to respond to fires and explosions in industry.

Local Fire Department

Inadequate Control Actions:

- Insufficient equipment for multiple tank explosion.
- Insufficient pressure to spray foam into the tank height
- Inadequate training for 11 tank fires caused by the vapor cloud explosion
- Lack of authority and coordination in multiple emergency response

Mental Model Flaws:

- Lack of experience, training and equipment to handle such a big scale major accident

State and Local Emergency Management

Inadequate Control Actions:

- Insufficient training and documentation.

Mental Model Flaws:

- Inadequate performance in hazard assessment that the facility posed a high hazard

Figure 4. CAST analysis for the local fire department and state and local emergency management

Figure 5 shows the CAST analysis for the government and regulatory agencies. According to the EPA and OSHA's legislation of that day, storage facilities like CAPECO were not seen as high-risk facilities; there was no need for comprehensive risk analysis. Although the EPA identifies facilities such as CAPECO as major damage facilities, the risk assessment required for these facilities under the Plant Response Plan requirements does not consider the probability of multiple tank releases as a worst-case scenario. At the time of the accident, there were deficiencies in legal scope under the Occupational Health and Safety Administration (OSHA) Process Safety Management (PSM) standard and the Environmental Protection Agency (EPA) Risk Management Plan (RMP). Tank terminal facilities were not required to carry out a risk assessment to manage flammable hazards on-site or to follow Recognized and Generally Accepted Good Engineering Practices (RAGAGEP).

The lack of coordination between the 43 federal, national and non-governmental organizations that responded to the CAPECO incident further complicated the emergency response. The multitude of organizations that intervened in the incident and the lack of coordination between them made it impossible to manage the emergency authorization systems.

The public living near CAPECO was evacuated. As there were no planned evacuation routes or shelters, inhabitants gathered in the streets. Thousands of gallons of oil and firefighting foams spilt into Malaria Creek, the water was polluted. As a result of the environmental assessment conducted by the EPA, the US Fish and Wildlife Service (USFWS) and the Puerto Rico Ministry of Natural Resources (PR DNR), it was determined that many creatures, including several legally protected species, died by being covered in oil.

National Regulatory Agencies
Inadequate Control Actions:
• Insufficient documentation and regulations
Mental Model Flaws:
• Lack of regulation in major ındustrial accidents.

Puerto Rico Occupation Safety Health and Administration (PR OSHA)
Inadequate Control Actions:
• Inadequate legislation of that day: petroleum product storage facilities were not seen as high-risk facilities.
• Inadequate legislation of that day: no need for comprehensive risk analysis.
• Inadequate legislation of that day: local fire department were not adequately equipped
Mental Model Flaws:
• Regulatory deficiencies
• Risk assessment deficiencies in multi-tank explosions

Environmental Protection Agency
Inadequate Control Actions:
• Lack of documentation to recognize multiple tank releases as a worst-case scenario
• Lack of a risk assessment to manage flammable hazards on site.
Mental Model Flaws:
• Regulatory deficiencies

Figure 5. CAST analysis for the government and regulatory agencies

4.4. Part 4: Identify Control Structure Flaws

In addition to the process model flaws, the authors identified systemic factors that affect system components and their interactions. These factors include communication and coordination as well as safety and organizational culture. Communication was crucial during the operations in the evacuation process. Since the operators required constant contact during manual loading process, they communicated via radio transceivers. Coordination was essential between tank operators and shift supervisors to ensure all necessary valve alignments and efficient switching arrangements between tanks. Communication and coordination between the planning department and the operation department were significant for carrying out the loading/unloading operations quickly. Overall health and safety can be compromised for fast discharge. Thus, the flaws in communication augmented the risk factor in the accident. Inadequate safety and organizational culture resulting in management's perception of a low-risk business despite poor design and operating conditions. Besides technical and engineering issues, safety culture and operational discipline are general overarching factors that affect the safety performance of a facility. Behavioral safety and safety culture are vital to the safe operation of the facility and accident prevention.

4.5. Part 5: Improvement program suggested improvements for the safety control structure

As a result of the CAST-based analysis of CAPECO accident applied in this study, direct and indirect causal factors related to the accident were determined. The direct cause that contributed to this accident was the lack of standardization of management and operational systems. Other major causes include:
(1) Absence of an independent "Automatic Overfill Prevention System"
(2) Insufficient documentation to recognize multiple tank releases as a worst-case scenario
(3) Insufficient reliability of critical equipment
(4) Flaws to detect a large amount of overflowed vapor cloud spread through the terminal area.

As a result, suggested improvements for the safety control structure are constructed in Figure 6. Instead of just trying to correct visible human errors, the control defects identified by the CAST analysis of this study produces the following safety recommendations to prevent such accidents in the future.

CAPECO
Overall System
• Perform proper risk analysis to recognize potential hazards and consequences and to take necessary precautions
• Revise and design the filling plan, ventilation, conveyance, communication systems before starting the transfer so that all system components support the transfer safely
• Install ex-proof/ATEX certified material in all part of the system
• Track gasoline loading with up-to-date electronic systems
• Establish a detailed database to monitor any activity at the facility
• Provide efficient and satisfactory level gauges of the tanks to detect the fuel discharge flow rate to the terminal
• Take necessary precautions when the "Automatic Overfill Prevention System" give alert and search for the potential causes
• Keep updated and systematic records of automatic prevention system measurements
• Installing motorized valves would eliminate the need to open large valves manually
Operators
• Give adequate training to all workers about the safety issues and monitor the impact of education
• Track operators according to their location in the facility
• Practice exercises for fire and evacuation
• Give special training to the control room operators in terms of coordination and communication for emergencies
Management
• Establish procedures to report unsafe activities
• Develop standards for safe working conditions
• Establish a safety culture among all employees
• Develop emergency management plans and implement evacuation and train all the operational and managerial staff
• Assemble a trained and experienced team for emergencies and provide specialized training and equipment to them

Figure 6. Suggested improvements for the safety control structure

5. Conclusion

Several lessons have been learnt as a result of this major industrial accidents. This accident demonstrated the need to adopt systems approach to identifying safety constraints. In this study, the accident was analyzed with CAST analysis based on CSB incident reports. Alternatively, a systems approach using CAST would not only look at what the operators did that contributed to the accident but, more important, why they did it. Since level gauges of the tanks and feedback computer system did not working, and there isn't an independent automatic overfill prevention system, the operators had been calculating tank levels manually. Sometimes, official results miss much of the information that could be useful in preventing such accidents in the future. Some of the many contributors to this accident were the design of the automation, the lack of an independent warning alarm and/or an automatic flow shut-off system.

In-tank terminals, where petroleum products are stored in a safety management system, and safe working procedures should be set out clearly and in detail. Insufficient safe working procedures budget cuts in training, maintenance, and equipment replacement often result in an accident. In addition, the control of the measures and the planning and coordination in the emergency response organization should be done properly. As a result, administrative personnel, maintenance personnel, and operation personnel should pay attention to safe working processes in risky activities to prevent similar accidents.

The most important point to be considered in order to carry out the CAST analysis successfully is modeling the existing safety control structure for this type of hazard. Leveson (2019) stated that "*The model of causality underlying CAST treats safety as a control problem, not a failure problem. The cause is always that the control structure and controls constructed to prevent the hazard were not effective in preventing the hazard. The goal is to determine why and how they might be improved.*" Similar accidents have occurred in the sector and control measurements were taken. The main purpose of this analysis is to determine why control measures are not effective and how they can be improved. Some of the controls may be general security applications, while others may be specific controls designed for certain situations. As the analysis progresses, the original hazards on the facility can be identified by performing a hazard analysis that goes beyond identifying the probabilities of failure with the questions generated.

Although the evaluation of each accident analysis is based on different reasons in itself, the results of this study and those of Li and coworkers (2020), who adopted the CAST analysis of the catastrophic underground pipeline gas explosion in Taiwan, have similarities in results according to the following respects: CAST enables the analysis of complex sociotechnical accidents, establishing the safety control structure and then updating it according to changes over time facilitates the investigation of accident causes.

CAST systematically revealed safety flaws. In the traditional accident causality analysis, someone or something is often blamed, and the analyst aims to identify a root cause. CAST, however, treats safety as a control problem. The results demonstrate that CAST allows analyzing the complex socio-technical accidents like multiple petroleum product tank terminal accident.

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Conflict of Interest

No conflict of interest was declared by the author.

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