APPLYING SYSTEM ARCHETYPES IN SYSTEM SAFETY ASSESSMENT

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Summary: *Modern safety critical systems are often referred as socio-technical systems in order to emphasize the inter-relatedness of "social" and "technical" elements in the systems. The operation of safety critical systems, for example a railway traffic management system, involves management of human activities and processes in the organizations, as well as the operation of the technical subsystems. The safety of these systems somehow is more than just about engineering their technical subsystems, because the concept of system has already been extended beyond the boundary from technical (computer-based) systems to include components such as social and managerial processes in the operation environment around the technical systems. As a result, what is needed in safety engineering is a new way of thinking – a systems thinking that capture the fundamental relationships of information to complexity so that engineers of every kind of enterprise can obtain the benefits and elude the obstacles of this change. In this paper, we demonstrated how an approach of systems thinking can help the safety analysis of social-technical systems. The highlight of this approach lies in the construction and analysis of system dynamics. The case study based on a metro accident in the US is adequate for the purpose of this feasibility research.*

Keyword: *Systems engineering; system archetypes; system safety; social-technical system; system dynamics.*

I. INTRODUCTION

Safety critical system is a class of engineered systems that may pose significant safety risks to their operators, the public and the environment.Safety is an emergent property of a system. As they are becoming more and more complex, safety of modern safety critical systems somehow is more than just about engineering a technical (mostly computer-based) systems. The concerns of system safety have already extended beyond the boundary of a technical system to include elements such as social and managerial activities.Researches on thesocial-technical approaches to systemsafety have been carried out since 1990s. Rasmussen (1997) classified of

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the socio-technical system involved in the control of safety in 6 levels: (1) the work and technological system, (2) the staff level, (3) the management level, (4) the company level, (5) the direct government regulators and industry association level, and (6) the overall Government level, and also pointed out that Because of the causal factors are inter-related and decisions of actors and the corresponding effects are usually separated in time especially in level 4-6, so the problem of safety complexity is particularly acute. As for theexplain of safety complexity,Senge [6] calls this dynamic complexity, which is different from detail complexity that complexity arising from large number of variables. Based on Rasmussen's classification, Sklet [4] compared of 14 important, recognized, commonly used methods of accident investigation, and thenconcludethat:

(1) Most of the methods is limited to Level 1 to Level 4 and not designed to analyze the dynamic complexity of systems but used to analyze the incident sequence and causal factors that are more immediate to the incident.

(2) Most of the methods view cause and effect linearly andare not designed to model changes in the system across time.

In order to explore the feasibility of a systemic improvementto the methods of accident investigation, we proposed to use the System dynamic to capture the dynamic complexity in a social-technical system. Since the causal loop diagrams can describe the inherent system characteristic properly, system behaviors, especially those related to the system safety, can be modeled by using feedback (causal) loops, stock and flows (levels and rates), and the non-linearity created by interactions among system components. Therefore behaviors over time (the dynamics of the system) can be captured by indicating positive and negative effects in a feedback loop diagram. We believe the application of this approach can provide a new ability of how to deal with the dynamic complexity of the socio-technical system in terms of its safety.

The rest part of paper is structured as follows. Section II presents the theoretical basis of this study, Section III is the methodology of this study. Section IV is a full Case study of a Subway Accident Analysis using the method that we proposed. The conclusions and discussions of this study are presented in Sections V.

II. CAUSAL LOOP DIAGRAMS AND SYSTEM ARCHETYPE

System dynamics is designed to help decision makers learn about the structure and dynamics of complex systems, to identify high leverage policies for sustained improvement, and to catalyze successful implementation and change. System dynamics provides a framework for dealing with dynamic complexity, where cause and effect are not obviously related. it is grounded in the theory of non-linear dynamics and feedback control, but also draws on cognitive and social psychology, organization theory, economics, and other social sciences [7].

Causal loop diagrams in system dynamics is a system approach that are designed to map the circular nature of cause and effect and demonstrate aspects of the system over time. Using this systemic method in accident analysis can help us focus on the interaction and interrelationships among system components at hierarchy levels on safety rather than on the single component failure, the systems archetypes are generic causal loop diagrams that describe the systemic structure of a wide variety of management situations. Senge [5] proposed 8 types of systems archetypes include (1)limits to growth, (2) eroding goals, (3) escalation, (4) success to the successful, (5) tragedy of the commons, (6) fixes that fail, (7) growth and under investment, (8) shifting the burden.

Systems archetypes aim to highlight the underlying structure of complex situations in a relatively simple fashion so as to facilitate identification of leverage in these situations [1]. This is why we use systems archetypesto find theappropriate certain patterns of relationships between system components to understand dynamic complexity.Take the 'shifting the burden' system archetype as an example, shown in Fig.1, it consists of two balancing processes, one addressing the symptoms and another addressing the fundamental causes of the problem in Fig 1 [5]. Symptomatic "solutions"can be very attractive to management, producing relatively quick positive results that focus on the symptoms and relieve the immediate pressure of the problem (B1). The second balancing process focuses on fundamental solutions to the problem that are more sustainable but also have a delay between implementation and results (B2). Failure to recognize this delay contributes to the tendency to focus on the symptomatic solution. Because of the high level attention of the quick fix (symptomatic solution), this behavior will produce the side effect that the fundamental problem will getting worse and reduced the ability of organization to solve the problem (R1). Systems thinking concludes that short-term efforts aimed at the symptoms can be useful, particularly to relieve the pressure as the delay from the fundamental solution is experienced, but long-term solutions to a problem must focus on the fundamental loop [1]. A more detailed case study will be explained using this archetypes in section VI.

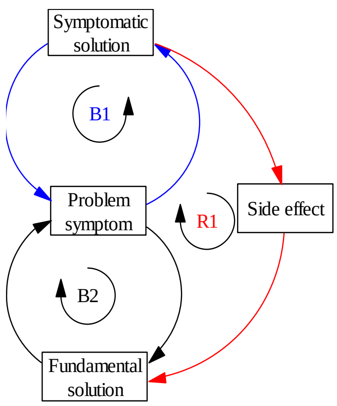

Fig 1. *A shift the burden archetype [5]*

III. APPLYING SYSTEM ARCHETYPES IN SYSTEM SAFETY ASSESSMENT PROCESS

Considering similar works [1], [2], we proposed an extended approach to system safety assessment and consists of four stages are summarized below in fig 2:

(1) Describe the system based onthe informationfrom various resources; and identifythe generic components of every associated organizations based on their responsibility and functions among the accident. It should be as detailed as possible to describe components and elements related to the accident like department, operators and the use of the information systems etc.

(2) Conduct a preliminary causal analysis with fault tree to identify the system elements and hazards, including the analysis of hardware failure, human error, software error, organization failure to obtain the logic of basic events that leading to the top events happen and laid the foundation of built a detailed causal loop diagram later.

(3) Model the system dynamics based on the fault tree analysis in a feedback loop diagram. Taking the "shifting the burden" system archetypes into considering, we detailed causal loop diagram to identify the "fundamental root" to cause the accident.

(4) use simulation and analysis of the feedback loop and their effects in causal loop diagram to conclude the most important factors that leading to the accident, find out the symptom and fundamental solutions of the problems and the side effects produced by the use of symptom solutions, in order to provides practical insights and help for managers to understanding of the accident in a systematic way.

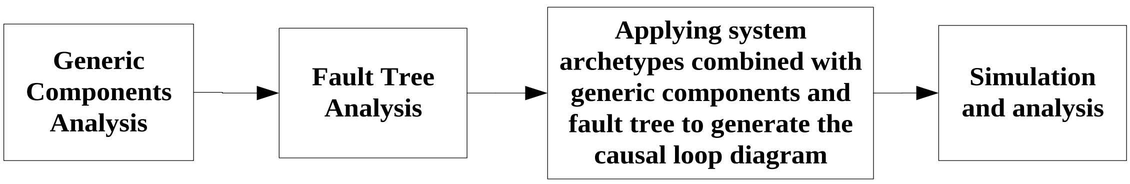

Fig 2. *Applying system archetypes in system safety assessment process*

IV. CASE STUDY: A SUBWAY ACCIDENTANALYSIS

In this section, we briefly introduced the general situation of the accident firstly, and then we follow the steps given in the third section to conduct the case study, Finally, a conclusion is reached by comparing the analysis results with the shortcomings of the other methods that we described at the start.

A. INTRODUCTION OF A COLLISION ACCIDENT

The accident used to build the accident analysis model was obtained from the National Transportation Safety Board [8]. The accident is about a collision of two Washington Metropolitan Area Transit Authority Train near Fort Totten Station. On Monday, June 22, 2009, about 4:58 p.m., eastern daylight time, inbound Washington Metropolitan Area Transit Authority (WMATA) Metrorail train 112 struck the rear of stopped inbound Metrorail train 214. The accident occurred on aboveground track on the Metrorail Red Line near the Fort Totten station in Washington, D.C. The lead car of train 112 struck the rear car of train 214, causing the rear car of train 214 to telescope into the lead car of train 112, resulting in a loss of occupant survival space in the lead car of about 63 feet (about 84 percent of its total length). Nine people aboard train 112, including the train operator, were killed. Emergency response agencies reported transporting 52 people to local hospitals. Damage to train equipment was estimated to be $12 million [8].

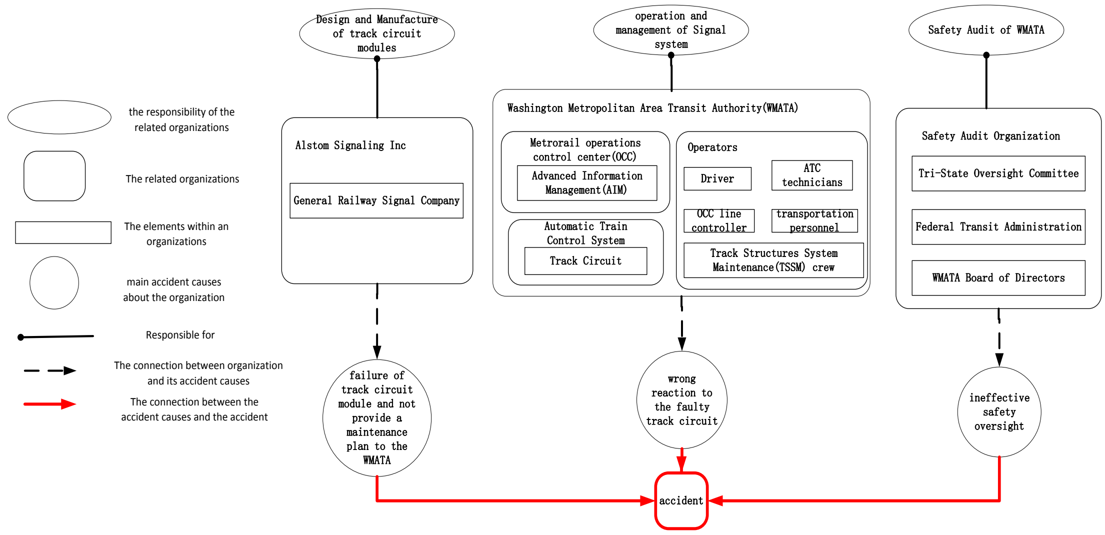

Fig 3. Generic components associated with the accident

B. FIRST STEP: GENERIC COMPONENTS ASSOCIATED WITH THE ACCIDENT

According tothe analysis steps given in the third section, we can use the NTSB report [8]as our source of information to get the generic components associated with the accident as shown in Fig.3.the organizations related to the accident include Alstom Signaling Inc, Washington Metropolitan Area Transit Authority (WMATA) and other Audit Organization, each part of the organization was composed of several sub-components, the oval on the top represent the responsibility of the related organizations(as the line with a circular end pointshowed in the diagram). The circlein the bottom represent the main accident causes about the organization (as the black dashed arrow and the red arrow showed in the diagram), the meaning of other notations as showed in Fig.3. for example,Alstom Signaling Inc as the manufacturer and designer of WMATA train control system, they were not tested the parasitic oscillation problem of their product at the time they were manufactured or installed and they were not considered the exhibited failure modesin their original design[8],so we can conclude that the responsibility of Alstom Signaling Incis design and manufacture of track circuit modules and the main causes of the accident about Alstom Signaling Inc is the failure of track circuit module and not provide a maintenance plan to the WMATA. The NTSB report [8] indicated the probable cause and the contributing to the accident, combined with the fault tree analysis and the system archetype of "shifting the burden", the cause would be regarded as the problem symptoms. Then we can analyze their symptomatic solutions and conclude the rootsolution on the basis of these symptoms.

C. SECOND STEP: IMPLEMENTING FAULT TREE MODELING A SUBWAY ACCIDENT ANALYSIS

Fault tree analysis is one of the mostimportant logic and probabilistic techniques used in system reliability assessment. The faults can be events that are associated with component hardware failures, human errors, software errors, or any other pertinent events. A fault tree depicts the logical interrelationships of basic events that lead to the top event of the fault tree. The top event of the fault tree is the event for which the failure causes will be resolved. It defines the failure mode of the system that will be analyzed.

We can find some basic informationfrom the NTSB report, like thenecessary condition of satisfied simultaneously thattwo trains rear-end include: two train occupied the same single-track railway and toward the same direction, Back-train faster than Front-Train, the collision avoidance systems failure and driver cannot avoid by braking.The collision avoidance systems include physical technical system and organization/human manual intervention system. Such as the use of signal lamp control system, automatic block signaling system, train state communication and control system etc. The organization/human manual intervention system include the Direct Manual intervention (proximate interventionabout the accident happened) and indirect Manual intervention (intervention associated with the accident during a period of time before the accident). The fault trees of the Subway Accident are shown in Fig.4 and broken into two parts. Due to space limitation reasons, we unfold only a part of the Collision avoidance technical system failure about the design flaw of the track circuit modules show in (a) and (b) in Fig 4, after compared with the accident report,we use the red color to show the most likely event that lead to the accident.For example, the most likely event that lead to the "Failure of detection & annunciation" is "Maintenance Specification not fit for purpose", the more deeper reason is not clear in the accident report, but maybe we can use the "poor safety management program" within Alstomto explain this, it may increase the pressure of software designer, make the staff in Alstom lack of or Unfamiliar with the effective regulation about design, test and commissioning. The "poor safety management program" can also make the designer lack of systematic training ornot have the capabilities to conduct a comprehensive safety analysis about the product. These basic event can as a clue to help us to build the more detailed causal loop diagram model and use the systemic thinking to make the further analysis of the cause of the accident.

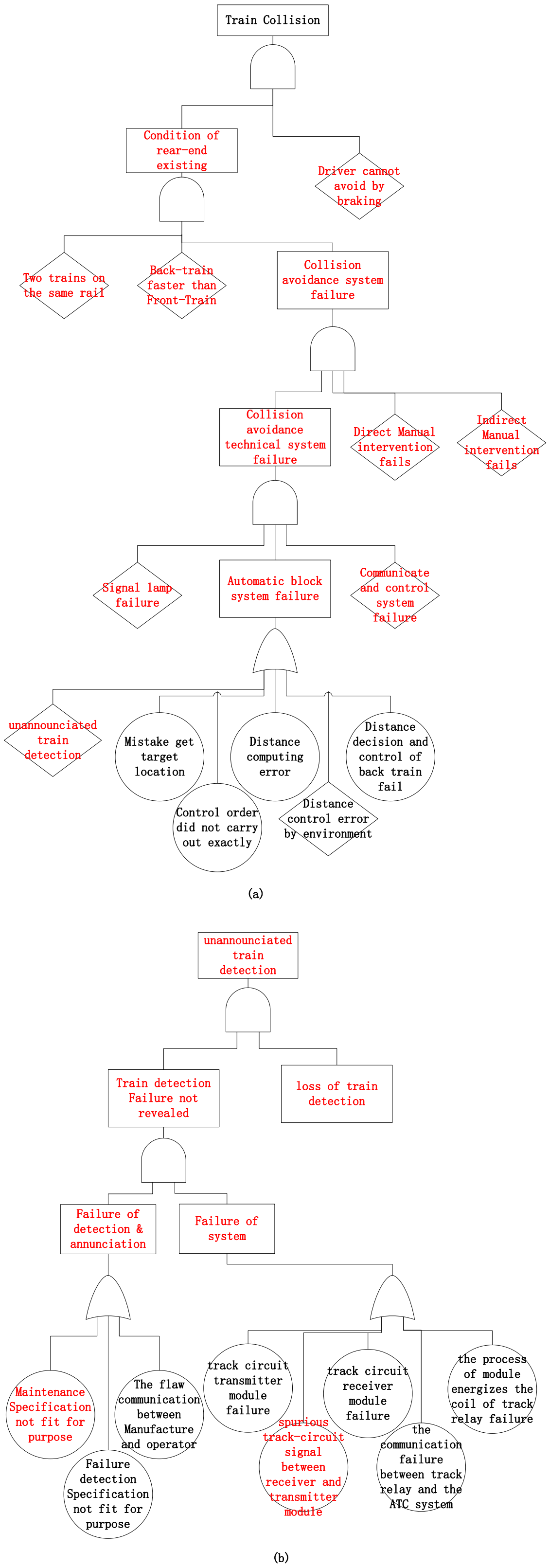

Fig 4. *The fault tree of the accident*

D. THIRD STEP: APPLYING SYSTEM ARCHETYPES, COMBINED WITH GENERIC COMPONENTS AND FAULT TREE TO BUILD THE CAUSAL LOOP DIAGRAM

1. Analysis ofthedesign flaw of the track circuit modules

We just use the part of design flaw of the track circuit modules analysis as an example to show our method we proposed above.

From the first step of our analysis in part B, we can conclude that one of the responsibility of GRS/Alstom is make sure the reliability and safety of its signal devices, so it should have established procedures to monitor the whole development process, ensure that the quality of products met national standardsand fulfilled the fail-safe principle. Another responsibility is provide a useful maintenance plan and procedure that would detect anomalies in the track circuit signal, such as parasitic oscillation, to the operator WMATA. Applying "shifting the burden" system archetypes, combined with generic components and fault tree analysis proposed in the first and second steps to build thedesign flaw of the track circuit modules causal loop diagram in Fig.5. Because we cannot get more information from the NTSB report, so We made some hypothesis in our casual loop diagram, For example, we can imagine that the poor safety management program in GRS/Alstom Signaling Incmightcause thepressure of design, make the software designer or technical engineer not familiar with the regulation about design, test and commissioning process or the organization lack of an effective regulation about design, test and commissioning, this makes the design flaw of the track circuit modules and also not provide a maintenance plan to the operatorto assurance safety at the same time. The poor safety management program can explained by the use "fly-fix-fly" or "trial-and-error" approach within GRS/Alstom Company.The "fly-fix-fly"approach means where accidents are investigated after they occur and the lessons learned are applied to modifications of existing systems and to the design of future ones. This approach is effective in industries where designs and technology are relatively stable over time, but it is less effective when new types of systems are built or the introduction of new technology leads to radically new designs for old systems [6].

At the time of the accident, the track circuit replacement program are in progress because the improvement of railway signaling system technics, track circuits had aged and some of the parts were failing. We cannot find the specific information about the GRS/Alstomparticipation in the program, but as the provider and manufacturer of the signaling system, GRS/Alstom failed to develop and implement periodic inspection and maintenance guidelines for WMATA [8]. this is one reason that lead to WMATA's failure to have a enhanced track circuit verification testprocedures to identify the malfunction of the track circuit.So it seems that GRS/Alstom have no thought to identify the potential hazards of the track circuits and only after the accident exposed the flaw of the track circuits problems. This is the after-the-fact philosophy of accident prevention and safety was only can obtained on the basis of experience accident. Therefore, the problem of "design flaw of the track circuit modules and do not have a useful maintenance procedure about detect anomalies to provide to the WMATA" was solved, at least in part, by the use of "trial-and-error" approach within Alstom as showed in fig.5. the "trial-and-error" approach which decreases the "poor safety management program in GRS/Alstom Signaling Inc "seems to solve the problem of "design flaw of the track circuit modules and do not have a useful maintenance procedure about detect anomalies to provide to the WMATA" and made up balancing loop B1.1,B1.2,B1.3. The more problems abound makes more use of the " trial-and-error" approach and the "trial-and-error" approach is just the symptomatic solutions that seems to control the problem, because the incentive to solve the root problem will disappear if the problem symptoms disappear, so we can see that "trial-and-error "approach is just the symptomatic solution of the problem.

In fact, as the technology is developing so fastandthe heavy competitive pressures fromdifferent product company, more and more enterprises planning to reduce product life cycles and improve market shares. Under this circumstances, Safety should be achieved by a proactive effort rather than experiencing accidents. The "trial-and-error" approach is only a short-term and temporarily solution, but what we really need is a long-term and root solution. One possible way is the use of system safety concept. System safety involves applying special management, hazard analysisand design approaches to prevent accidents in complex systems. It is a planned, disciplined, and systematic approach to preventing or reducing accidents throughout the life cycle of a system. Rather than relying only on learning from past accidents or increasing component integrity or reliability, an attempt is made to predict accidents before they occur and to build safety into the system and component designs by eliminating or preventing hazardous system states [6].

So if the concept of system safety applied in GRS/Alstom Signaling Incbefore the accident, it would have balanced the design task and production safety, identified hazards and introduced an acceptable safety level into the system prior to actual design and production, that means the system hazards would have been identified in a timely way and evaluated and then eliminated, or controlled to an acceptable level. "Application of system safety concept" is long-term fundamental solution to the problem. The fundamental solution feedback loop is shown in B1.4 in fig 4. Table 1 showed the explanation and hypothesis in B1.1-B1.4.

For the problem of defective design and do not have a useful maintenance procedure to provide to the WMATA, the "trial-and-error" approach is a traditional solution. It may be very attractive to management and produce quick responses to the problem. However the symptomatic solution is only a temporarymeasure. The accident disclosed the equipment with design defects triggered by parasitic oscillation in the track circuit modules and the problem of the maintenance procedure, but we do not want to rely on further accidents to identify other defects. Increasing use of the "trial-and-error" would cause the unintended side effect of losing "capability of safe design and to produce complete rules" which in turn would decrease the opportunity for the "application of system safety concept" approach, make the organization more dependent on the "trial-and-error" approach, and ultimately trap it into using only the symptomatic solution. The reinforcing loop R1.1 showed the side effects reinforced the symptomatic solution and the fundamental corrective measures were used less and less.

However, if use the application of system safety concept, the increase of the problem will also make the use of the fundamental solution increase, then there would be a decrease in the problem and keeping the loop in balance again.

From the above analysis, we could also conclude that the probable cause of the collision about the GRS/Alstom Signaling Inc isthe design of the flawed track circuit modules and failure to provide a maintenance plan that would detect anomalies in the track circuit signal, and this conclusion in accordance with the NTSB report.

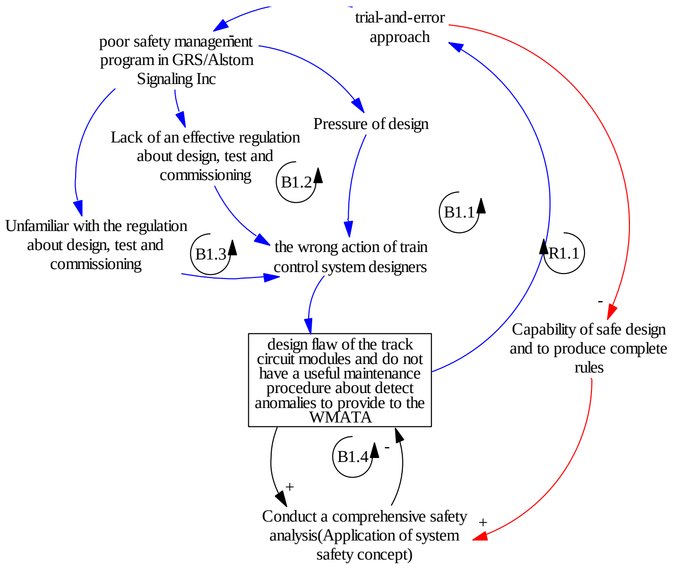

Fig 5. *Causal loop diagram for the collision Accident about design flaw*

Table 1. *The explanation and hypothesis in B1.1-B1.4*

Loop	Hypothesis	Explanation
B1.1	GRS/Alstom Signaling Inc use the "trial-and-error" approach in software design process	GRS/Alstom use the "trial-and-error" approach in software design process makes the Poor safety management program within GRS/Alstom,then lead to the pressure of design of staff and the wrong action of train control system designer
B1.2	GRS/Alstom Signaling Inc use the "trial-and-error" approach in software design process	GRS/Alstom use the "trial-and-error" approach in software design process makes the Poor safety management program within GRS/Alstom,then lead to the lack of effective regulation about design,test and commissioning of staff and the wrong action of train control system designer
B1.3	GRS/Alstom Signaling Inc use the "trial-and-error" approach in software design process	GRS/Alstom use the "trial-and-error" approach in software design process makes the Poor safety management program within GRS/Alstom,then lead to the unfamiliar with the regulation about design,test and commissioning of effective regulation of staff and the wrong action of train control system designer
B1.4	GRS/Alstom Signaling Inc do not apply the application of system safety concept in software design process	GRS/Alstom Signaling Inc do not apply the application of system safety concept in software design process

2. Simulation

Because we analyzed above were just soft causal loop diagrams and we need some work about quantitative SD models to prove our method is a more efficient way for providing insights to the scholars, practitioners, private or public decision-makers. So we use the design flaw of the track circuit modules above as an example to construct the quantitative model with the SD code VENSIM. The stock and flow diagram of design flaw of the track circuit modules as showed in fig.6 and the result of simulation are showed in fig 7 and fig 8.

As showed in fig 7, the “trial-and-error” approach is a short-term fix and shifting the problem away: it eliminates for some time the design flaw symptoms, but at the same time it diverts attention away from fundamental decisions of application of system safety concept. This policy results in a vicious side effect loop: it increases the level of “trial-and-error” approach (blue line) while decreasing the available application of system safety concept (red line), so the problem symptom of design flaw also increases (green line). Fig 8 showed that if use more of the fundamental solution of application of system safety concept (red line) from the start, the level of “trial-and-error” approach (blue line) and the problem symptom of design flaw(green line) will all decreased over time.

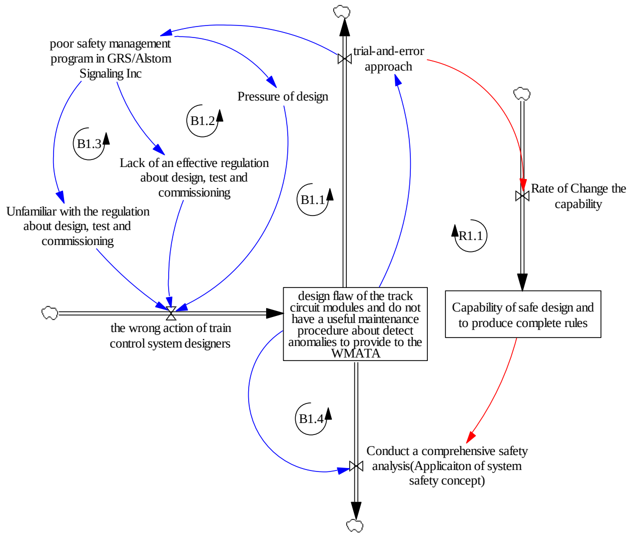

Fig 6. *The stock and flow diagram of design flaw of the track circuit modules*

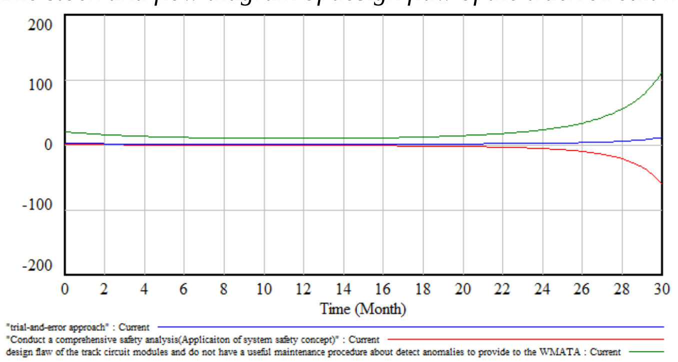

Fig 7. *Thesimulation result of design flaw of the track circuit modules*

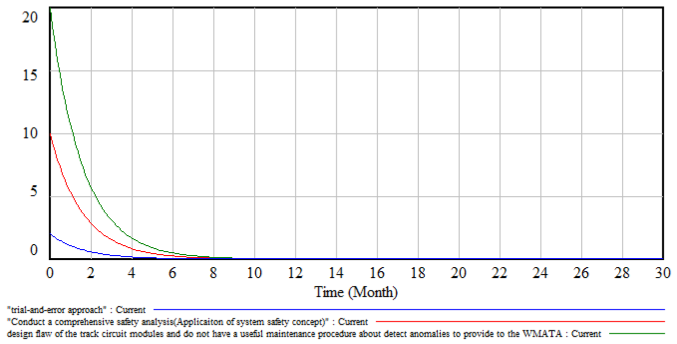

Fig 8. *Thesimulation result of design flaw of the track circuit modules (high value of application of system thinking concept from the start)*

3. Summary

According to the NTSB report about the information that before the accident, include some public hearing and interview, Weconclude and analysis the main cause of the accident about the design flaw of track circuit modules that in accordance with the conclusions of the report. We usethe rectangles to represent the main problem symptoms in the accident in our causal loop diagram. It can show us not only the elements and the interaction between them, but also identifies the contributors relating to every element.The element "trial-and-error" approach as a dominated element interacted with the whole system and as a symptomatic solution cannot resolve the fundamental problems.With the “shifting the burden” archetype, when a symptomatic solution is applied to the problem, it just can obtain a short-term and superficial effect. We can easily find that the symptomatic solution leads to side effects in the diagram. The side effect feedback loops are of the reinforcing type which means that it can growth or decline in exponential way when not influenced by other factors. Otherwise, the simulation result can also prove the analysis in causal loop diagram and providing a more deep insight to the stakeholders.

In the above analysis, we use the system dynamics theory to analyze the causes of the accident systematically. Because the system dynamics is based on non-linear and feedback control theory, taking the factor of evolution of the system over time into account, specifically suitableto solvethedynamic complexity problem of system that cause and effect are not obviously related.Soit can properly solve the problem of thedynamic complexitythat we proposed at the beginning of the article that most methods cannot do.

V. DISCUSSION AND CONCLUSIONS

A. DISCUSSION

As for some other researchers, Banson applied the system archetypes to analysis the quality of crop produce in Ghana and showed us that subsidizing fertilizer and quality seeds is an quick fix to the problem but the fundamental solution is Integrated resource Management [9]. Nguyen applied the system archetypes to analysis the Problems in Cat Ba and showed us that

International aid is an quick fix to the problem but the fundamental solution is Local and national capacity building [10],Goh applied the system archetypes to analyze the Bellevue hazardous waste fire accident, showed us the non-linear complicated interactions between multiple factors from the system angle and how the reactive safety culture influence the whole system [1].Yunxiao fan Proposedan approach to analyze a train accident in China, applying system archetypes in system safety assessment [2], the analysis include three steps: (1) use the investigation report as the information source integrated with system archetype of "shifting the burden" to find the factors that caused the problem symptoms. (2) Find the symptomatic solutions of the problem symptoms. (3) Find the fundamental solutions and the influence of side effects of symptomatic solutions to it. On the basis of these researcher and through improvement of their methods, we propose a more systematic way to applying systems archetypes for system safety assessment, which use of the fault tree and system dynamics theory, combined with the generic components of every associated organizations, the basic events in fault tree analysis and "shifting the burden" system archetypes to establish detailed causal loop diagram of the system to analysis.

B. CONCLUSIONS

The difference between this article and NTSB report is: The NTSB report revealed us a information source to understand the accident by linear causation models. But we use the concept of system thinking and causal loop diagrams in our research to develop a systematic model that showed us the circular nature of complex systems. We adopted the "shifting the burden" archetype to identify the symptomatic and fundamentalsolution of the problem. On the surface, the symptomatic solution is a "trial-and-error" approach that can keeping the problem under control, but in fact, the real problem still there and even get worse. On the contrary,the fundamental solutions of the problem are systemic, not only can help us to identify the underlying contributory factors in the accident report ,but also show the direction of what countermeasures we can take to prevent the accident. Through the use of the concept of system thinking and causal loop diagrams we can improve the safety management capacity and design a more effective safety culture. The main contribution of this article is provide practical insights for managers through the case study. First, the fundamental solution to Alstom is apply the concept of system thinking in system design that in accordance with the recommends from NTSB report to conduct a comprehensive safety analysis of its audio frequency track circuit modules to evaluate all foreseeable failure modes that could cause a loss of train detection over the service life of the modules so as to insure against the likelihood of the train control system failure. Second, the causal loop model and the result of simulation is a reminder to managers about the importance of adopting systemic views during critical decision making. The developed model can facilitate comprehension of the wider system and contributes to decision making.

C. LIMITATIONS AND FUTURE WORK

The study was primarily reliant upon documentary evidence contained within the NTSB report and the causal loop model was developed based upon some literatures and the researchers' insights to provide a framework to understand and describe an accident. As the study mainly focused on the angle of GRS/Alstom Signaling Inc organizations to analyze the cause and solution of the accident, so maybe some other elements were not considered in the model and need to be improved and modified in different situations.

Except for the shifting the burden archetypes, there are also other seven system archetypes: (1) limits to growth, (2) eroding goals, (3) escalation, (4) success to the successful, (5) tragedy of the commons, (6) fixes that fail, (7) growth and under investment [5]. So maybe we can use other system archetypes to understand the non-linear complexity and dynamics of safety management problems and provided systemic insights into these safety issues in our future work. As for system archetypes can describe many kinds of system structures in different management scenario and can show us the common patterns of behavior of systems, through the use of different system archetypes to model the safety problem can provide more systemic insights and prevent the accident from the source.

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