SYSTEMS THINKING APPROACH TO MODERNIZATION AND MAINTENANCE OF AGING INLAND WATERWAYS INFRASTRUCTURES

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ABSTRACT

This research explores a systems thinking approach for aging Inland Waterways Infrastructure with the intent to analyze the effectiveness of modernization and maintenance at the system level. Authors hypothesize that current practices to allocate resources for modernization and maintenance needs are not effective at increasing the utility of the system as a whole.

The systems thinking approach proposed in this paper develops a holistic examination of how components of the system are related to each other. The key to this approach is examining the interrelationships between modernization and maintenance impact factors; such as usage frequency, failure frequency, future demand, deterioration, condition interdependencies and effects of each factor on the system as whole. Previous researchers have analyzed each modernization and maintenance impact factor separately; however, interrelationships between these factors and the effects at the system level have not been explored. The approach presented in this paper provides a decision-making framework for optimal usage of resources for the aging inland waterways infrastructure, thus providing a long-term solution to modernization and maintenance issues and increasing the availability and reliability of the system.

Keywords: Optimization, decision making, resource allocation, asset management, budget prioritization

INTRODUCTION

For more than two centuries, the U.S. inland waterways infrastructure has been a vital national asset. This asset is utilized by many stakeholders; including nearby communities, transportation groups, power plants, and biologists. Although the inland waterways infrastructure is critical to our nation's economy and social well-being, the modernization and maintenance of these assets have not received the required attention. Lack of modernization and maintenance of the aging inland waterways infrastructure create a danger for losing this important asset ultimately causing disruptions on transportation services, flood management, water and power supplies, and wildlife.

Over the past decade, improved asset management techniques have been implemented; however, limited resources force authorities to practice linear-thinking approaches resulting in short term solutions. A systems thinking approach should be considered which will assume the system as a whole and examine how the components of the system are related to each other, thus offering a holistic explanation of the problem which will lead to a holistic solution. If a systems thinking approach is applied to modernization and maintenance activities, then the reliability and availability of the systems as a whole could be increased.

This paper describes factors that impact the modernization and maintenance of the system. By analyzing the interrelationships between these factors, the areas requiring attention can be demonstrated. The approach described in this paper can prioritize modernization and maintenance resource allocation decisions. This approach is useful especially considering the limited resources.

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BACKGROUND

U.S. Inland Waterways are comprised of approximately 12,000 miles, 192 lock sites and 238 chambers. The major usage of the waterways is to provide transportation of goods. A single tow of 15 barges carries the same quantity of goods as 870 tractor trailer trucks which makes the waterway transportation much more efficient and environmental friendly (Grier 2004). Other usages of this national asset include, but are not limited to, flood management, water and power supply, and protection of wild life. Figure 1 shows part of the U.S. Inland Waterway System.

Figure 1. U.S. Inland Waterway System.

Failure of this navigational infrastructure is mainly caused by its locks and dams which mostly are managed by the U.S. Army Corps of Engineers (USACE). Most of these locks and dams were constructed during the 1930s, making the system more than 80 years old. Aging of this system is not a problem if a sufficient modernization and maintenance is completed. However, limited resources and current large system maintenance backlog increases unavailability and decreases reliability of the system. As the system's unavailability increases and reliability decreases, transportation services are impacted the most; The cost of transported goods increases.

Literature Review

Modernization and maintenance of aging infrastructures has been an attractive topic for many researchers and practitioners. Many approaches, frameworks and models have been developed to address individual parts of the critical question; how can the negative impact of aging inland waterways infrastructure be minimized?

Researchers have considered resilience, failure frequency, interdependencies after failure, deterioration, traffic flow, and alternative scheduling simulations. Each researcher attempted to resolve a part of the problem; Baroud et al. (2013) quantified resilience with regards to vulnerability and recoverability, and provided two approaches to measure each components contribution to system resilience. Baroud's 2013 study addressed the resilience part of the problem. Later in 2014, Baroud provided a Bayesian kernel model to predict failure frequency which addressed the unpredictability of system failure. Folga et al. (2009) provided system-level approach that considers interdependencies within the system after disturbances. They provided analysis for alternative transportation modes in case of system not being available and analyze economic effects. A condition and reliability prediction model for the system was provided by Grussing et al. (2006), using Weibull probability distribution. Smith et al. (2010) developed a simulation model which focused on solving the traffic congestion part of the question by providing clear picture of vessel movements and analyzing the impacts of alternative scheduling.

As mentioned, researchers have analyzed each modernization and maintenance impact factor separately; however, interrelationships between these factors and their effects at the system level have not been explored.

Current Practices Review

Decreasing availability and reliability of aging inland waterways has been a challenge for the USACE. During 2008, an effort was initiated to capture the risk of failure on a 5X5 relative risk matrix cube. This effort was followed by development of Operational Condition Assessment (OCA), which is an effort to separate mission critical assets from non-mission critical ones and assess their conditions (USACE 2015). During 2011, Asset Management, which deployed OCA at a regional level, was implemented. Building on asset management practices, USACE started using economic impact rather than tonnage for the consequence on the 5X5 risk matrix cube (TRB 2015). Asset Management Portfolio Analytics (AMPA) report was published by USACE in 2012. This report discusses that USACE’s asset management approach is to prioritize resource’s failure and economic consequence at a regional level (Valverde 2012).

Current practices provide a risk-informed approach to search for best resource allocation at a regional level and do not consider the effect of many factors at the system level and their interrelationships among each other. Unfortunately, current practices are restricted significantly by the available resources and forces USACE to make decision on only economic consequences of a failure.

APPROACH

Authors conducted an extensive literature research, current practices analysis and publicly available data analysis to identify gaps and generate a list of factors that have impact on modernization and maintenance needs at the system level. This paper utilizes a new approach, systems thinking, to examine the available data to understand interrelationships between all impact factors and each impact factor’s influence at the system level.

What is Systems Thinking?

INCOSE (2012) describes systems thinking as a circular causation. Per INCOSE 2012, one of the main characteristics of systems thinking is that it recognizes the primacy of interrelationships and it is a way of thinking that recognizes the primacy as a whole. MITRE (2014) describes systems thinking in a similar way, considers systems thinking as “a framework for solving problems based on the premise that a component part of an entity can best be understood in the context of its relationships with other components of the entity, rather than in isolation”. The authors recognize the systems thinking description similarities between these well-known systems engineering authorities. In order to solve a problem and create a long-term solution, one must analyze the system as a whole and understand the interrelationships between components of the system.

Modernization and Maintenance Requirement Impact Factors

After extensive review of the literature, interviews with experts and examination of available data, the authors determined the modernization and maintenance impact factors. Figure 2 illustrates these modernization and maintenance impact factors. These factors determine the level of modernization and maintenance needed for a lock and dam system. In order to make decisions which will lead to long term solutions, it is critical to understand the interrelationships between these factors and their effects in the greater picture.

The following sections further explains each of these impact factors.

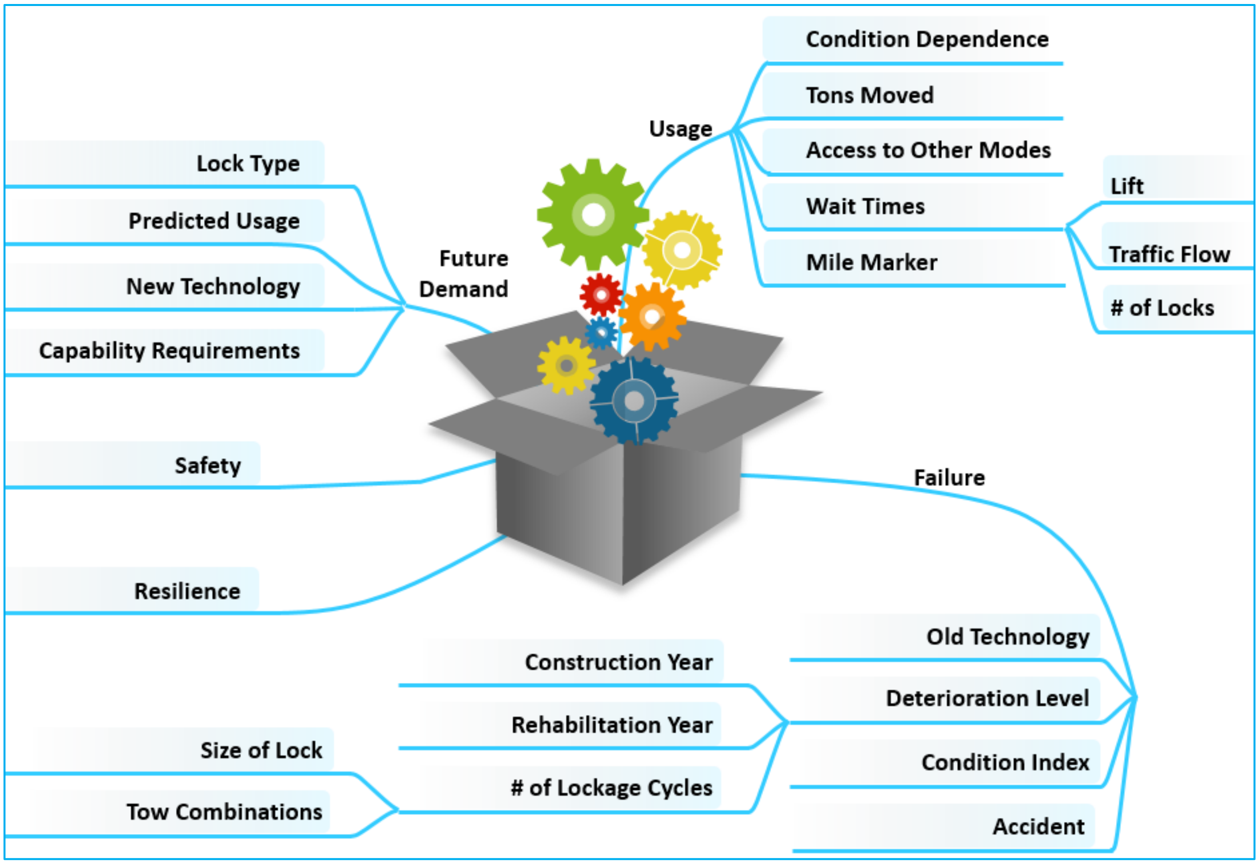

Figure 2. Modernization and Maintenance Impact Factors.

Failure

Failure is the time when system is unavailable. Failure frequency and probability of failure is a major element when deciding modernization and maintenance activities allocation. Figure 3 provides a detailed outline of system failure impact factors.

Figure 3. System Failure Impact Factors.

Failure of the system is impacted by existing old technology, deterioration level, condition index and probability of accident.

Old technology increases the possibility of failure. Mechanical structure is no longer efficient to handle as many lockage cycles.

The condition index indicates the physical condition of a component. It is assigned after a visual inspection.

Deterioration level has the biggest impact to possibility or frequency of failure. Construction year, which is also referred as age, is an indicator of system deterioration, but not the only indicator. Rehabilitation year and number of lockage cycles must also be considered. The authors assume age of the system reduces to zero after a major rehabilitation. Number of lockage cycles influences deterioration level because it demonstrates how much the lock is physically used, thus indicates the need for maintenance.

Usage

Usage of the component indicates the logistic importance, thus the consequences in case of failure. Figure 4 provides usage impact factors.

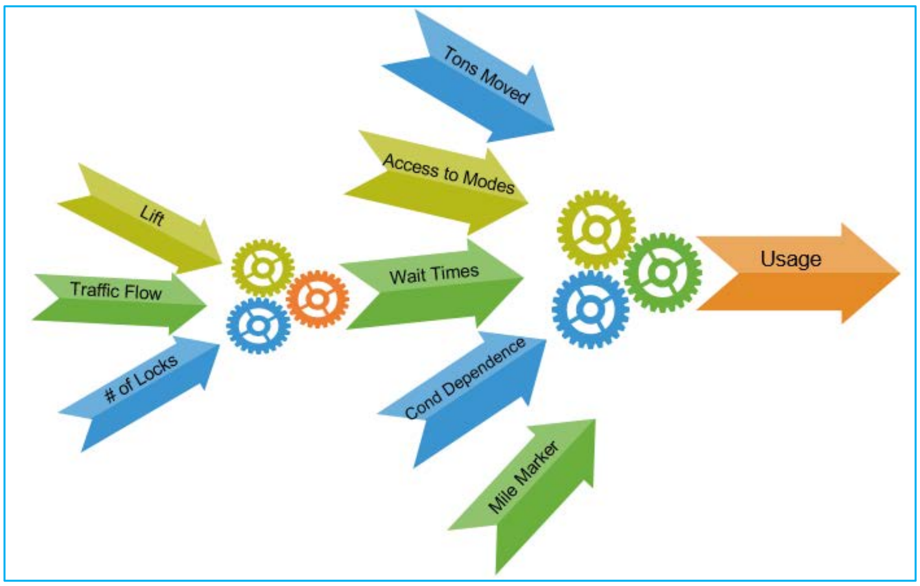

Figure 4. System Usage Impact Factors.

Tons moved is the indicator of traffic flow. The higher traffic flow is more important than the location of the component and of greater consequence.

Access modes is the component location's access to other transportation modes to transport the goods. If a location has no access to railroad or highway, the importance of the location increases because in case of failure, the consequence will be higher.

Wait times are influenced by lift of chamber, traffic flow and number of locks. Wait times will increase as the usage and logistic importance of component increases.

Lift is the depth of the lock chamber. Higher lift requires more time for the chamber pool to fill which will influence lockage times, thus increasing wait times.

Number of locks directly influences wait times. If there is only a single lock, then wait times will be higher than if there is main and auxiliary locks or multiple locks. The consequence of failure will also be greater if a failure occurs at a single lock.

Future Demand

Future demand is how much and under what conditions the system will be used in the future. As it is outlined in figure 5, future demand of the system has 4 factors that it is influenced by; future capability requirement, new technology, predicted usage, and lock type. These factors must be considered while making decision on modernization and maintenance of the system.

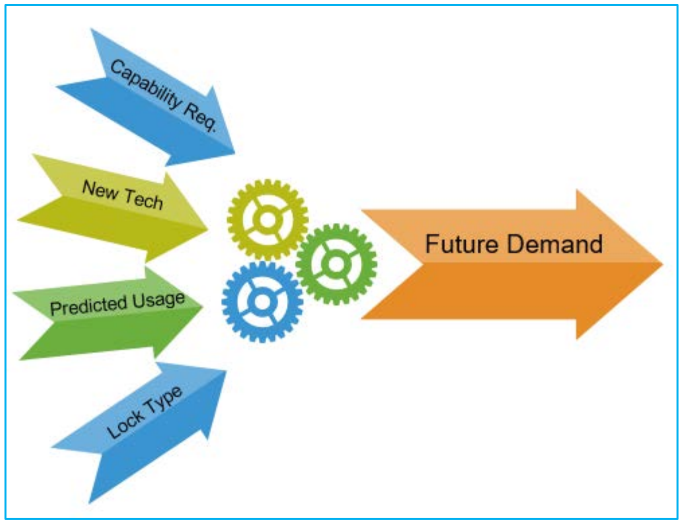

Figure 5. System Future Demand Impact Factors.

New technology has two perspectives; for the system and for the system users (i.e. vessels). Inland waterways were designed decades ago, while users were still using steam powered boats and were capable of pushing up to 6 barges at a time. However, now, with the advanced technology, diesel powered boats could push up to 15 barges.

Future capability requirements will be set by the new technology related to system users. As the system users moved from steam powered boats to diesel powered boats, capability requirements changed.

Predicted usage is important to understand how much more traffic flow is expected from the component and which corridors of the system will be used more often. It is also important to understand what kind of commodities will be transported through the system.

Lock type impacts the modernization and maintenance of the system from two difference aspects. The first aspect is how quickly can traffic flow, as mentioned previously in this paper. The second aspect is the size of the chamber. With new technology, now boats can push more barges thus now the size of the tow combination is increased. Future applications must be considered.

Resilience

Resilience is how quickly a system can recover after a failure. Because the inland waterways system is a cascading system, resilience of one component has great influence on the availability of the system. If a single lock is out of order, the traffic flow will be at a stop for all locks before and after.

Safety

Safety is at risk when a lock chamber is too small for a tow combination and the tow combination has to be broken into pieces to accommodate the size of the lock. In those instances, towboats and crew must be idling at the lock which creates a possibility for man overboard or towboat crushing into the lock walls. When deciding if a component of the inland waterways systems need modernization and maintenance, increasing safety must be one of the goals.

RESULTS

The USACE provides public data on number of vessels using a particular lock, the lock type, dates and number of lockage cycles, vessel directions, lock closure dates, durations and causes (scheduled or unscheduled) via the Lock Performance Monitoring System. The data provided is used to demonstrate interrelationships between impact factors. It is no surprise that there is a dynamic relationship between failure, usage, future demand, resilience and safety.

Correlation analysis of available data revealed that as the system's age increases, deterioration level increases; however, system's age is not the only indicator of deterioration level increases. Deterioration level of a less aged component could be more than that of a more aged component, if the less aged component had more lockage cycles. Lockage cycles have a bigger impact on deterioration level than the age of component. Failure and usage are directly related to each other; as failure occurs, consequences are greater depending on the usage, and logistic importance of the component. Usage and logistic importance have many indicators, as mentioned previously. If a component is at a location where there are many tons moved or located at busy corridor, meaning it has a high usage, then the failure will have a bigger impact on it. Increase tons moved will have influence on wait time on the lock which is also related to how fast the goods move through the lock. If the component has a single lock, then the traffic will depend on it and effects of failure will be greater. Future demand is directly related to modernization of the system. The system must be prepared for the future needs of the users. As capability requirements increase, new technology efforts must increase.

CONCLUSIONS

Based on preliminary correlation examination of impact factors via available data and the new approach presented in this paper, a systems thinking approach considering all impacts of modernization and maintenance requirements will optimize decision making processes for asset management of aging infrastructures.

Further research is proposed to use the approach discussed in this paper and stochastic modelling to optimize modernization and maintenance of aging infrastructures, and generate an objective assessment method.

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CITATION

Alkas, Z., Franz, A.Y., and Wasek, J.S. "System thinking approach to modernization and maintenance of aging inland waterway infrastructures," *Proceedings of the Western Dredging Association Dredging Summit & Expo, Vancouver, BC, Canada,* June 26-29, 2017.

ACKNOWLEDGEMENTS

This material is developed from proposed dissertation submission to the George Washington University in partial fulfillment of the requirements for the Doctor of Philosophy degree.

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