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Infrastructure system of systems integrity

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Keywords

infrastructure, integrity, systems, system

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Abstract

Infrastructure systems typically consist of technical structures comprising of physical and operational components of interrelated constituent systems forming what is now known as *system of systems* (SOS). The complexity and uncertainty of unforeseen events that are inherent characteristic of infrastructure systems makes it impossible to predict undesirable emergent behaviours that could push the operation of such systems away from their intended purposes. Infrastructure systems present numerous challenges throughout their lifecycles. This paper addresses one of these challenges that is presented during operation, when managers need to report 'how well' the system is performing and find ways to address the consequences of unexpected events that often degrade the intended performance. This paper adopts a definition of *system integrity* (SI) to assess the SI for each constituent system and then combines them into the overall SI for the SoS. The proposed method is based on the on-going operational performance, safety and resilience of the constituent systems and applies the Analytic Hierarchy Process (AHP) to create a quantitative value derived from experience-based qualitative assessment. In this method, firstly the key performance indicators (KPI) for each of the agreed assessment criteria for operational performance, safety and resilience are defined and individually assessed. Then the KPIs for each of the three criteria are weighted relatively to each other to obtain the overall assessment for operational performance, safety and resilience for each individual system. These three criteria are also compared and weighted to determine their level of contribution to the SI for the system which is then calculated. The method is then expanded to assess SI for SoS and applied into a hypothetical urban transport system for illustration purposes

Key Words

Infrastructure, system of systems, system integrity, urban transport

Introduction

Infrastructure refers to the fundamental facilities and systems serving a country, city, or area, including the services and facilities necessary for its economy to function (Sullivan and Sheffrin 2003). It typically characterises technical structures such as transport systems which can be defined as the physical and operational components of interrelated systems (Fulmer 2009). So, Infrastructure is naturally a set of interrelated systems forming what is now known as *system of systems*. Although there is no single definition for *system of systems* (SoS), there is a consensus that SoS exhibit 'emergent behaviours' that result from the interaction of constituent systems that are operated and managed independently (Nielsen, Larsen et al. 2015). Another definition for SoS is provided in (Mayk and Madni 2006) as "*a collection of systems that were originally designed as stand-alone systems for specific and different purposes but that have been brought together within the SoS umbrella to create a new capability needed for a particular mission".* Man-made SoS, like infrastructure systems, are designed to exhibit desirable behaviours which are the objectives of the system in the first place.

Infrastructure systems present numerous challenges throughout their lifecycles, from concept definition, planning, design and construction through operation and final disposal. One of these challenges, the subject of discussion in this paper, is presented during the operation phase when managers need to assess 'how well' the system operates and will continue operating in the future. It is also under the responsibility of infrastructure managers to predict and address the consequences of unexpected events that can degrade the intended quality of operation. The many components of infrastructure systems and often constituent systems of the infrastructure SoS need to operate in consonance to achieve the desired state of *well-being* and *integrity*.

When applied to a system *integrity* implies the quality of 'wholeness' and 'soundness'. The NASA Systems Engineering handbook (Kapurch 2010) defines the *system integrity* (SI) as "*the efficient composition of components/subsystems into a whole that offers the required functionality and achieves specific goals*". The term *system integrity* is widely used in the data security context and is defined as "*the accuracy and consistency of stored data, indicated by an absence of any alteration in data between two updates of a data record"* (American Heritage Dictionary 2017). SI is integral to the overall system development life cycle and systems engineering processes have been used for decades to assess SI during system development to assure compliance of design and implementation with specification (Madni and Sievers 2014).

According to (Neches and Madni 2013) the complex systems today have to satisfy a number of requirements such as affordability, reliability, adaptability, security, and resilience. Different kinds of system have also different factors that contribute to the overall SI. For example, Sturza (Sturza 1988) assesses the quality of a navigation system by examining the faulty measurement sources and suggests that the integrity of system output can be assured by monitoring the integrity of the system which is defined based on two factors: probability of missed detection and the probability of false alarm. In another study Jayles et. al (Jayles, Chauveau et al. 2016) work on identifying and reducing the abnormal behaviour of an orbitography system to avoid degrading the accuracy and performance. SI in this study is defined by two factors: availability of the data and identification of the questionable data. Another example provides approaches for managing a water distribution and disinfection system (Trussell 1999) and the author claims that safeguarding the SI is the key to assuring the wellbeing of the system, where SI is defined based also on two factors: primary disinfection and residual maintenance. Umeadi et. al (Umeadi and Jones 2008) also have attempted to develop a process for monitoring the SI of a pipeline system as they believe this is associated with disruption to supply, damage to the environment and cost to the company.

Despite definition of *system integrity* in the fields of systems engineering and data security, there is no standard agreed definition for *system integrity* in the context of infrastructure systems in the published literature. Furthermore, there is no agreed definition of what factors should be considered to assess the integrity of infrastructure systems. The definition provided by (Sullivan and Sheffrin 2003) states that infrastructure systems provide services and facilities. Whether the infrastructure system provides water, electricity, transport, telecommunications or other services there are always costumers that should be satisfied with the delivery of services reflected by the operational performance of the system. Operational performance should be one of the factors to be considered to assess the SI of infrastructure systems. In addition to operational performance, safety is an important aspect in infrastructure systems which should minimise risks that could threat lives and well-being of their customers. Safety should be the second factor that contributes to the integrity of infrastructure systems. The third factor suggested by this paper is resilience. Resilience is the capacity of the system to recover from disruptions and continuing operating in adverse and sometimes unpredictable conditions (Pyster, Olwell et al. 2017). Neches describes resilient systems as follows: "*A resilient system is trusted and effective out of the box in a wide range of contexts, easily adapted to many others through reconfiguration or replacement, with graceful and detectable degradation of function*" (Neches 2011).

When applied to infrastructure systems, this paper suggests that *system integrity* is determined by a combination of operational performance, safety and resilience. In the context of infrastructure systems the ideal *system integrity,* when the system achieves its maximum integrity, can be defined as the *"state of a system where it is performing its intended functions safely without being degraded or impaired by* *changes or disruptions in its internal or external environments"*. When the system achieves its perfect condition its *system integrity* is 100% or 1.0. The system, however, may operate at lower levels of integrity caused by changes or disruptions internal or external to the system. Therefore it is important to assess and monitor SI to make sure the system is operating within acceptable levels and to envisage ways to improve SI in the event of unexpected situations.

SI can be assessed by using different methods specific to the system of interest and its relevant factors which may not be directly applied other systems. For example, the method used for assessing the integrity of a water distribution system proposed by (Trussell 1999) cannot be used for assessing the integrity of the pipeline system as conducted in (Umeadi and Jones 2008). In an attempt to reduce this problem this paper proposes a method to assess *system integrity* of infrastructure systems that could be extended to other kinds of systems. The method applies the Analytic Hierarchy Process (AHP) (Saaty 1994) to create a quantitative value derived from quantitative and experience-based qualitative assessments to determine the SI of infrastructure systems and SoS by considering three criteria based on operational performance, safety and resilience. Each of these three factors is assessed by considering their specific 'key performance indicators' (KPI): Operational KPIs (KO), Safety KPIs (KS) and Resilience KPIs (KR) that are combined in a weighted manner using AHP. As an example, KOs could include KPIs for quality of service, reliability, availability, maintainability and cost; KSs could include KPIs for number and severity of accidents; and KRs could include KPIs for level of disruption and time for recovery to acceptable levels. The proposed method is then applied to a hypothetical urban transport system for demonstration purposes.

This paper is organized as follows. Section 2 discusses SI for one single system and proposes a method for assessing SI of infrastructure systems using AHP. Section 3 introduces SI for SoS, proposes a method to assess SI of SoS and presents a hypothetical example applying the proposed method. Section 4 concludes the paper and suggests future work.

Assessing system integrity

From the context and definition presented in the introduction SI reflects the performance infrastructure system during operation. SI can be quantified by assessing how well the system achieves the three criteria of operational performance, safety and resilience. The proposed method to assess SI of a single system comprises of the following six steps:

Step 1 Define the 'Key Performance Indicators' (KPI) used to asses each of the three criteria: operational performance (O), for safety (S) and for resilience (R). Each criterion potentially has many KPIs and each KPI should have a method to be measured or assessed.

Step 2 For each criterion compare pairwise its KPIs to obtain their relative importance using AHP Priority Matrix. This will provide the relative weight of each KPI for a given criterion.

Step 3 Using the methods defined in Step 1 assess the actual value for each KPI in a scale from 0.0 to 1.0, the latter meaning that the KPI has been fully achieved.

Step 4 Using the weights obtained in Step 2 and the actual value for each KPI the overall operational performance, safety and resilience of the system are calculated.

Step 5 Using AHP Priority Matrix compare pairwise the three criteria to obtain the relative weight of each criteria in the context of SI.

Step 6 SI is calculated using the actual values for operational performance, safety and resilience obtained in Step 4 and the weights from Step 5.

Step 1

It is fundamental that the KPIs for operational performance (KOs), safety (KSs) and resilience (KRs) are well defined and understood and there are methods to measure or to assess how well the system is achieving each KPI. The definition of KPIs and their methods of assessment are out of scope of this paper. It is assumed that the engineers, managers and other people in the organisation are capable of defining and assessing their pertinent KPIs.

Step 2

The Analytic Hierarchy Process (AHP) is a framework of multi-valued logic based on the innate human ability to use information and experience to construct ratio scales through paired comparison (Saaty 2000). The object of the analysis is arranged in a hierarchic network structure that breaks down the whole into its smaller parts thus allowing paired comparison. Paired comparison is done using 'The Fundamental Scale' of nine levels 1–9, shown in Table 1 (adapted from (Saaty 1994) Table 3.1 and (DiMario, Boardman et al. 2009) Table II).

Table 1 – The Fundamental Scale of AHP

Intensity of Importance	Definition	Explanation
1	Equal importance	The two components contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one component over the other
5	Strong importance	Experience and judgement strongly favour one component over the other
7	Very strong importance	One component is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one component over another is of the highest possible order of affirmation
2, 4, 6, 8	For comparisons between the above values	Interpolation of a compromised judgement

The objective of the AHP is to compare all components in the system of interest to determine the weight of importance or contribution of each component to the whole. Although AHP has formal mathematical foundation it is simple to use and algebraic calculations are easily performed with the aid of mathematical software tools. AHP shows that if the system of interest has 'n' components, the pair comparison constitutes an *n x n* square matrix named Priority Matrix.

Considering that the operational performance criterion is described by 'n' KPIs which a team of experienced people should be able to discuss and hopefully agree with how each KPI is more or less important to the overall performance. The assessment is done by comparing each operational KPI with the other 'n-1' KPIs and placing the comparison in a square matrix, as shown in Figure 1. The diagonal of the matrix is '1' as it corresponds to the comparison of a KPI with itself. The components $C_{i,j}$ above the diagonal are numbers from '1 to 9' chosen from the 'the fundamental scale of AHP' while the components below the diagonal are the inverse of the components above because they correspond to the inverse comparison, i.e. *'how is KPI_i more important than KPI_j?'* and *'how is KPI_j more important than KPI_i?'.*

The relative weight or priority of each KPI is the normalised principal eigenvector, obtained from the maximum eigenvalue, of the Performance Priority Matrix (Saaty 1994) and can be calculated using mathematical tools such as *MATLAB* or other similar tools. The Operational Performance Vector for the component 'c' (OPVc), equation (1), corresponds to the weight (W) of importance of each of the 'n' KOs (Operational KPIs) to the overall performance. OPVc needs to be normalised so that the some of its components is equal to '1.0', as shown by equation (2).

	KO_1	KO_2	…	KO_{n-1}	KO_n
KO_1	1	$C_{1,2}$	…	$C_{1,n-1}$	$C_{1,n}$
KO_2	$1/C_{1,2}$	1	…	$C_{2,n-1}$	$C_{2,n}$
…	…	…	..	…	…
KO_{n-1}	$1/C_{1,n-1}$	$1/C_{2,n-1}$	…	1	$C_{n-1,n}$
KO_n	$1/C_{1,n}$	$1/C_{2,n}$	…	$1/C_{n-1,n}$	1

Figure 1 – The Operational Performance Priority Matrix for one single system component

$$\boldsymbol{OPVc = (WOc_{KO1}, WOc_{KO2}, \ldots WOc_{KOn-1}, WOc_{KOn})} \quad (1)$$

$$\boldsymbol{WOc} = \sum_{i=1}^{n} \boldsymbol{WOc}_{\mathbf{koi}} \quad (2)$$

OPVc should be normalised so that ***WOc = 1.0***

The same process is repeated for the other two criteria of safety and resilience to obtain the relative weight of their respective KPIs.

Steps 3 and 4

In practice the components contributing to the system performance may not be performing at their nominal capacity reflecting the 'actual performance' (AP) that could be between 0% and 100%. The level of 'acceptable performance', 'degraded performance' or 'not operational' can be defined by AP ranges and thresholds. AP is calculated or estimated in accordance with predefined and agreed methods. The set of values of 'how well KPIs are achieved' form the Actual Operational Performance Vector (AOPVc) and the product of OPVc and AOPVc transposed is the operational performance (OPc) of that system component, as shown by equation (3).

$$\boldsymbol{OPc = OPVc \times AOPVc^T} \quad (3)$$

If the system has 'm' components contributing to the overall operational performance, the same approach is used to calculate the operational performance of each component and to assess the level of importance of these components to the overall system performance. The latter requires to develop a 'm x m' Priority Matrix to obtain the Operational Performance Vector for the system (OPV), equation (4), which has 'm' components. The Actual Operational Performance Vector for the system (AOPV), equation (5), contains the actual performance for each component in the system. The overall system operational performance (OP) is obtained from the product of OPV and AOPV transposed, shown in equation (6).

$$\boldsymbol{OPV} = (WOP_{C1}, WOP_{C2}, \ldots WOP_{Cm-1}, WOP_{Cm}) \quad (4)$$

$$\boldsymbol{AOPV} = (AOP_{C1}, AOP_{C2}, \ldots AO_{Cm-1}, AOP_{Cm}) \quad (5)$$

$$\boldsymbol{OP = OPV \times AOPV^T} \quad (6)$$

$$\text{where } \boldsymbol{OP} = \sum_{i=1}^{m} \boldsymbol{WOP_{Ci} \times AOP_{Ci}}$$

Once again the same approach is used to assess the contribution of each component in the system to safety and resilience. The method assumes that safety and resilience are properties of the system provided by design that can be assessed by safety and resilience KPIs, respectively KSs and KRs, through agreed methods. Starting with safety, a Priority Matrix is constructed in the same way to obtain the Safety

Performance Vector (SPV), equation (7). The Actual Safety Performance Vector (ASPV), equation (8), is obtained by assessing how well each KS is being met. The overall safety performance (SP) is the product of SPV and ASPV transposed, as shown in equation 9.

$$\boldsymbol{SPV} = (WSP_{C1}, WSP_{C2}, \dots WSP_{Cm-1}, WSP_{Cm}) \quad (7)$$
$$\boldsymbol{ASPV} = (ASP_{C1}, ASP_{C2}, \dots ASP_{Cm-1}, ASP_{Cm}) \quad (8)$$
$$\boldsymbol{SP = SPV \times ASPV^T} \quad (9)$$
$$\text{where } \boldsymbol{SP = \sum_{i=1}^{m} W\, SP_{Ci} \times ASP_{Ci}}$$

Resilient systems can be achieved by capabilities within system or as an emergent property through collaboration with other systems. The first is achieved by design provided by redundant or backup components that are part of the system (Pyster, Olwell et al. 2017). The second is achieved by emergent properties of SoS and will be discussed in the next section. Resilience performance can be assessed using the same methods as for operational and safety performances, as shown by equations (10) to (12).

$$\boldsymbol{RPV} = (WRP_{C1}, WRP_{C2}, \dots WRP_{Cm-1}, WRP_{Cm}) \quad (10)$$
$$\boldsymbol{ARPV} = (ARP_{C1}, ARP_{C2}, \dots ARP_{Cm-1}, ARP_{Cm}) \quad (11)$$
$$\boldsymbol{RP = RPV \times ARPV^T} \quad (12)$$
$$\text{where } \boldsymbol{RP = \sum_{i=1}^{m} W\, RP_{Ci} \times ASP_{Ci}}$$

Steps 5 and 6

Finally, it is also need to assess the level of importance of each of the three assessment criterion of operational performance, safety and resilience to obtain the overall SI and the same approach is used once again, now in the form of a 3 x 3 Priority Matrix shown in Figure 2. Equation (13) shows the System Integrity Vector (SIV) and equation (15) shows the overall System Integrity (SI) as the multiplication of SIV and the transposed Actual System Integrity Vector (ASIV), equation 14, which contains the actual operational performance (O), safety (S) and resilience (R) for the system.

	O	S	R
Operational (O)	1	P_S	P_R
Safety (S)	$S_P = 1/ P_S$	1	S_R
Resilience (R)	$R_P = 1/ P_R$	$R_S = 1/ S_R$	1

Figure 2 – The Priority Matrix for System Integrity

$$\boldsymbol{SIV} = (w_O, W_S, w_R) \quad (13)$$
$$\boldsymbol{ASIV} = (O, S, R) \quad (14)$$
$$\boldsymbol{SI = SIV \times ASIV^T} \quad (15)$$
$$\text{where } \boldsymbol{SI = W_O \times O + W_S \times S + W_R \times R}$$

It is reasonable to assume that safety would have a higher level of importance over operational performance and resilience. Operational performance could be considered a little higher than resilience because resilience is not expected to be activated frequently and some level of operational performance degradation may be acceptable. However, the weight of operational performance, safety and resilience should vary from system to system and should be estimated accordingly.

Assessing system of systems integrity: an example

Urban transport is a *system of systems* often comprising multi-mode forms of transport, a shared ticketing system, roads, parking and tolls. The example used to apply the System Integrity Assessment method to a SoS is a hypothetical simplified urban transport system comprising of a network of trains and buses sharing a common ticketing system. Each of the constituent system (Rail, Bus and Ticketing) is independently managed and operated, and collaborates with the other systems to achieve the overall urban transport service, as shown in Figure 3.

The three constituent systems work together to achieve three objectives of operational performance (O), safety (S) and resilience (R) that are not equally shared by the constituent systems. Safety is very important for trains and buses but not as important for the ticketing system because the latter does not present the same level of safety risks as the other two. Operational performance also depends of different kinds of collaboration between the constituent systems. The flow of passengers between trains and buses and through the ticketing system is important for meeting the revenue KPI. Without Ticketing neither the Rail or Bus systems would be able to collect revenue and without passengers from train and buses the Ticketing system would not be able to collect its share for the ticketing service.

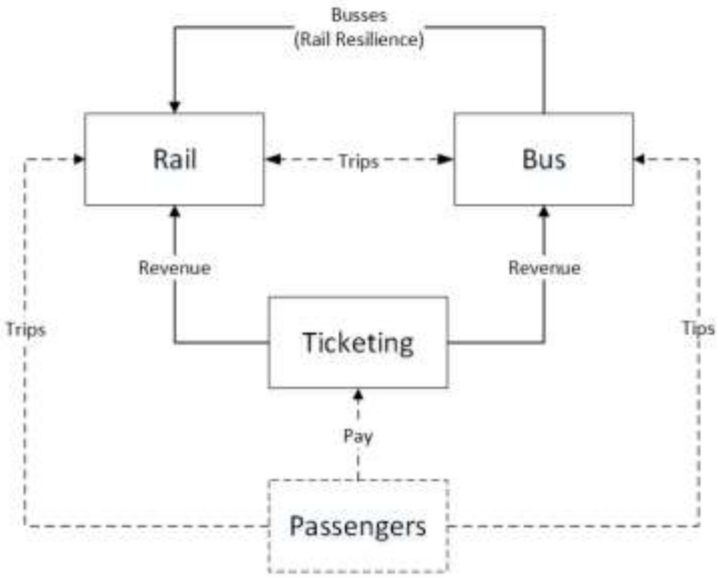

Figure 3 – Hypothetical Urban Transport SoS

For the example here presented the Bus system collaborates with the Rail system to provide resilience. Buses can replace trains for a particular section of the Rail line when it is not operating due to failure or maintenance. The inverse, however, is not possible because in practice trains are unlikely to be able to replace buses in a significant portion of their routes.

To assess the SI of this urban transport SoS the method proposed in section 2 is extended with four additional steps.

Step 7 Estimate the level of importance of each constituent system for each of the three criteria of performance, safety and resilience using AHP supermatrix approach.

Step 8 Estimate the relevance of each of the three criteria relevant for each of the three constituent systems is assessed using AHP supermatrix approach.

Step 9 Calculate the relative weight of each constituent systems and each individual criterion by stabilising the AHP supermatrix.

Step 10 Calculate the SI for the SoS using the individual SI for each constituent system applying steps 1 to 6 and the weights calculated in step 9.

Steps 7 and 8

To assess the SI of this urban transport SoS it is needed to weight the contribution of each constituent systems to the overall SI and also weight the three criteria of operational performance, safety and resilience in the context of the SoS as a whole. AHP can be applied to systems with feedback loops where individual components and assessment criteria influence each other (Saaty 1994). AHP has been used in many complex systems applications including the investigation of emergent properties of SoS (DiMario, Boardman et al. 2009), the decision-making process to develop sustainable infrastructure (Diaz-Sarachaga, Jato-Espino et al. 2017) and to model a software-intensive acquisition for a naval helicopter (Peculis, Rogers et al. 2007).

The bottom left part of the supermatrix in Figure 4 answers the question *'what is the level of importance of each constituent system for each of the three criteria of performance, safety and resilience?'*. The top right part of the supermatrix answers the question of *'what of the three criteria is more relevant for each of the three constituent systems?'*. The weights placed in the supermatrix reflect the characteristics of the urban transport SoS and could have been estimated using Priority Matrices as discussed in section 3. Here, however, the weights were estimated directly for simplicity and hypothetical nature of this example.

	Ra	Bu	Tk	O	S	R
Rail (Ra)	0	0	0	0.5	0.6	0.5
Bus (Bu)	0	0	0	0.3	0.3	0.4
Ticketing (Tk)	0	0	0	0.2	0.1	0.1
Operational (O)	0.4	0.4	0.6	0	0	0
Safety (S)	0.5	0.5	0.2	0	0	0
Resilience (R)	0.1	0.1	0.2	0	0	0

Figure 4 – Hypothetical Urban Transport SoS Supermatrix

Step 9

The sum of the weights of each column of the supermatrix is equal to 1.0 which is characteristic of 'stochastic supermatrix' which can be stabilised by raising it to power, i.e. multiplying the matrix by itself several times, until all the columns have the same values for each block, as shown in Figure 5.

	Ra	Bu	Tk	O	S	R
Rail (Ra)	0	0	0	0.5457	0.5457	0.5457
Bus (Bu)	0	0	0	0.3114	0.3114	0.3114
Ticketing (Tk)	0	0	0	0.1429	0.1429	0.1429
Operational (O)	0.4286	0.4286	0.4286	0	0	0
Safety (S)	0.4571	0.4571	0.4571	0	0	0
Resilience (R)	0.1143	0.1143	0.1143	0	0	0

Figure 5 – Hypothetical Urban Transport SoS stabilised Supermatrix

The three weights shown in the bottom left of the matrix correspond to W_O, W_S and W_R of equation (13) and are used to calculate the SI for each constituent systems as per equations (14) and (15). The three weights in the top right of the matrix are the relative weights for the SI of each constituent system and form the Urban Transport System Integrity Vector (UTSIV) as per equation (16).

UTSIV = (w_{Ra}, W_{Bu}, w_{Tk}) (16)

Step 10

Finally, the SI of the urban transport SoS is calculated by multiplying UTSIV by the Actual Urban Transport System Integrity Vector (AUTSIV) transposed, as per equation (18), where ASI_R, ASI_B and ASI_T are respectively the actual values for SI for Rail, Bus and the Ticketing constituent systems calculated using the method presented in section 2.

$$\boldsymbol{AUTSI\ V= (ASI_{Ra}, ASI_{Bu}, ASI_{Tk})} \quad (17)$$

$$\boldsymbol{UTSI = UTSIV \times AUTSIV^{T}} \quad (18)$$

$$\text{where } \boldsymbol{UTSI = W_{Ra} \times ASI_{Ra} + W_{Bu} \times ASI_{Bu} + W_{Tk} \times ASI_{Tk}}$$

Conclusions

This paper proposed a method to assess *system integrity* for systems and *system of systems* using AHP. The method relies on the human ability of performing pairwise comparison and in the capability of engineers and managers to define and assess key indicators of operational performance, safety and resilience for the systems they are responsible for. The method also assumes that engineers and managers would be able to agree on KPIs, their respective methods of assessment and the on the relative weights for each of their assessment criterion.

The proposed method allows infrastructure professionals to identify KPIs and components in the system or SoS that have higher influence on SI which in turn should have higher priority for improvements, issues identification and resolution.

The authors acknowledge that uncertainty and lack of confidence can be present in the process of developing Priority Matrices and relative weights between the elements in the system. Techniques like fuzzy hierarchical analysis (Buckley 1985) can be used to address uncertainty in the process of assessing *system integrity* and will be subject of future work.

The proposed method is yet to be tested in practice which becomes an important component of future work which could also address larger systems and SoS with more components, constituent systems, interdependencies and assessment criteria set. In the meantime the authors hope that this paper will be able to motivate infrastructure managers and decision-makers to consider the application of this method into their own real systems and SoS. It is of great importance that these professionals reflect upon the definition of *system integrity* in the context of their specific systems, which should lead to the identification of system components, constituent systems, assessment criteria and weight of relevance, influence and importance. The method here proposed should provide guidance for a good start and could be adapted to other systems with different and specific SI factors and KPIs.

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