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A METHODOLOGY OF TRIAGE FOR BRIDGES IN DEPOPULATING SOCIETY: MODELING BASED ON POPULATION AND NETWORK CONNECTIVITY

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Abstract. Developed countries like Germany and Japan, and many of their municipalities currently have large debts that will likely increase over time. These debts may never be repaid because debt repayment per capita will increase as a result of decreasing populations. It has become difficult for them to maintain many of their existing bridges because of large debts. Given the challenges faced with maintaining these bridges, it is necessary to formulate plans that may include discontinuing the maintenance on certain bridges. Therefore, this study proposes the use of a triage methodology for managing bridges (e.g., highway bridges) much like the triage methodology used by medical institutions to handle large numbers of patients after a severe disaster. More specifically, the proposed methodology makes decisions based on whether or not to build a new bridge after an existing bridge has reached the end of its lifespan and is decommissioned by evaluating factors such as cost and convenience. This is done by establishing a virtual network comprising of links made up of bridges that span across towns. This study proposes models and simulates this social problem by virtual networks and virtual bridge data, which can then be used to derive an optimal solution.

Keywords: bridge, demographic energy, depopulating society, network connectivity, simulation, triage.

1. Introduction

Developed countries like Germany and Japan, and many of their municipalities currently have large debts that will likely increase over time. Furthermore, these debts may never be repaid because debt repayment per capita will increase as a result of decreasing populations. Many social infrastructures were actually built during high-growth periods, but have resulted in problems with maintenance in the present time because these societies are ageing. This study therefore, focuses on the maintenance problems of social infrastructures, bridges in particular. The issue at hand is whether or not bridges that were built as a result of population demand during a time of rapid population growth are still presently needed when these societies now face a decreasing population. This issue was not a problem so long as these countries and municipalities experienced high economic growth and a growing population which allowed for sustainable debt. During low-growth periods and periods of decreasing population, debt can approach unsustainable levels, which will only worsen over time. In the meantime, old highway bridges will continue to deteriorate resulting in increasing operating and maintenance costs (Hao 2010). Furthermore, some of these bridges may not be rebuilt when they approach the end of their service life due to the inability to acquire the required funds as a result of increasing debt. Therefore, an evaluation methodology of determining whether a bridge should be maintained or decommissioned is needed. Many people in these developed countries have recently started to pay attention to this problem. A triage methodology to evaluate each bridge is one of the countermeasures that can be used to solve this problem (Kuriyama *et al.* 2014). Originally, a triage methodology was used by medical institutions to handle a large number of patients after a severe disaster. Governments and municipalities with a continuously decreasing population will be able to make decisions by using this methodology. The proposed triage methodology evaluates each bridge using the corresponding town population and town network connectivity. More specifically, the proposed methodology makes decisions on whether or not to build a new bridge, after the existing bridge has

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reached the end of its lifespan and is decommissioned on the basis of cost and convenience. This decision making process is done by establishing a virtual network comprising of links made up of bridges that span across towns to identify bridges that must be maintained and bridges that could be decommissioned. If a decommissioned bridge is not rebuilt, existing travel routes must change which could interfere with the current passage of people and commodities. At the same time, the concept of demographic energy to quantify these circumstances is used in this study. Demographic energy is calculated for the overall virtual network from town populations and distances. This triage methodology checks all patterns for the decommissioning of each bridge using an integrated time value of demographic energy, the operation and maintenance costs of the bridge, and the demographic energy around each unit cost as an index for decision making. This triage methodology can then be applied to other countries that may face decreasing population and/or rising debt in the future.

2. Previous research

There is a substantial amount of research on the operation and maintenance plans for bridges. Some studies calculate the deterioration curve of the bridges as structures (Kaito *et al.* 2003; Liu, Frangopol 2006; Madanat *et al.* 1995; Ranjith *et al.* 2013), whereas others estimate the longevity of highway bridges (Tamakoshi *et al.* 2004a, 2004b), or propose operation and maintenance policies based on repair plans (e.g., preventative maintenance) (Frangopol *et al.* 2001; Hudson *et al.* 1997; Society for Road Structures Conservation, Road Management Technology Center ed. 2008; Lethanh *et al.* 2015; Ohshima 2009).

In addition, studies focus on life-cycle costs and budgets considering the rate of deterioration of the bridges (Barone 2014; Kong, Frangopol 2005; Niki *et al.* 2005). Still others optimize repair timeframes for multiple bridges using game theory (Kita, Chikata 2010).

Much research has gone into road network planning, in which studies use graph theory to evaluate road networks connecting cities (Erath *et al.* 2009; Furuyama 1988; Ünsalan *et al.* 2012).

Table 1. Estimated results for bridge lifespans by decade of construction in Japan (Tamakoshi *et al.* 2004a)

Year of construction	Average lifespan, years	Standard deviation, years
1921–1930	40	10
1931–1940	40	10
1941–1950	30	10
1951–1960	60	20
1961–1970	70	20
1971–1980	70	20
1981–1990	100	30
1991–2000	100	30
2000–	100	30

However, the aforementioned studies were conducted with the purpose of expanding road networks and increasing their convenience in a period of population growth. Thus, no studies have investigated how to reduce road networks in the event of a population decrease.

3. Characteristics of this study

(1) Aspects to focus on during the operation and maintenance of bridges in a society with a declining population.
(2) This study does not exclude inconvenient choices where new bridges would not be built after the deteriorative bridge is decommissioned.
(3) Aspects for determining connectivity based on graph theory by using virtual networks as examples.
(4) Aspects for preparing evaluation indices based on demographic energy.

4. Premises for this study

(1) Actions to be taken are based on the concept that conducting administrative services within the range of tax revenues is the financially sound condition for the nation as well as the municipalities, while continuing to increase debts is definitely not a sound condition.
(2) An emphasis is placed on the proposal of the methodology, and explanations are provided based on a simplified virtual network diagram prepared by schematically representing the relationships between cities and bridges.
(3) The lifespan of a bridge is considered to be 100 years, based on previous research (Table 1). Bridges are immediately decommissioned upon reaching the end of their lives, followed by a decision on whether to build a new bridge. When new bridges are constructed, the decommissioning and new construction both take place within the same year.
(4) Simulate period is the next 100 years.
(5) This study assumes preventative measures in the repair of bridges. Furthermore, this study does not consider future technological innovation, and instead assume the continued use of existing repair and construction technologies.

5. Research methodology

5.1. Research flowchart

Figure 1 shows the research flowchart.

5.2. Step-by-Step explanation

STEP 1: Creating an outline of virtual network.

This study presents a discussion based on a simplified virtual network that is comprised of nodes (towns) and links (bridges and roads). First, three types of networks, i.e., 1 – Basic network; 2 – Radial network, and 3 – Ring network, are prepared (Fig. 2).

The circled numbers represent town numbers. The lengths of radial link arrangements, as well as ring links (diagonal links), are considered to be 1.4 against 1 for links

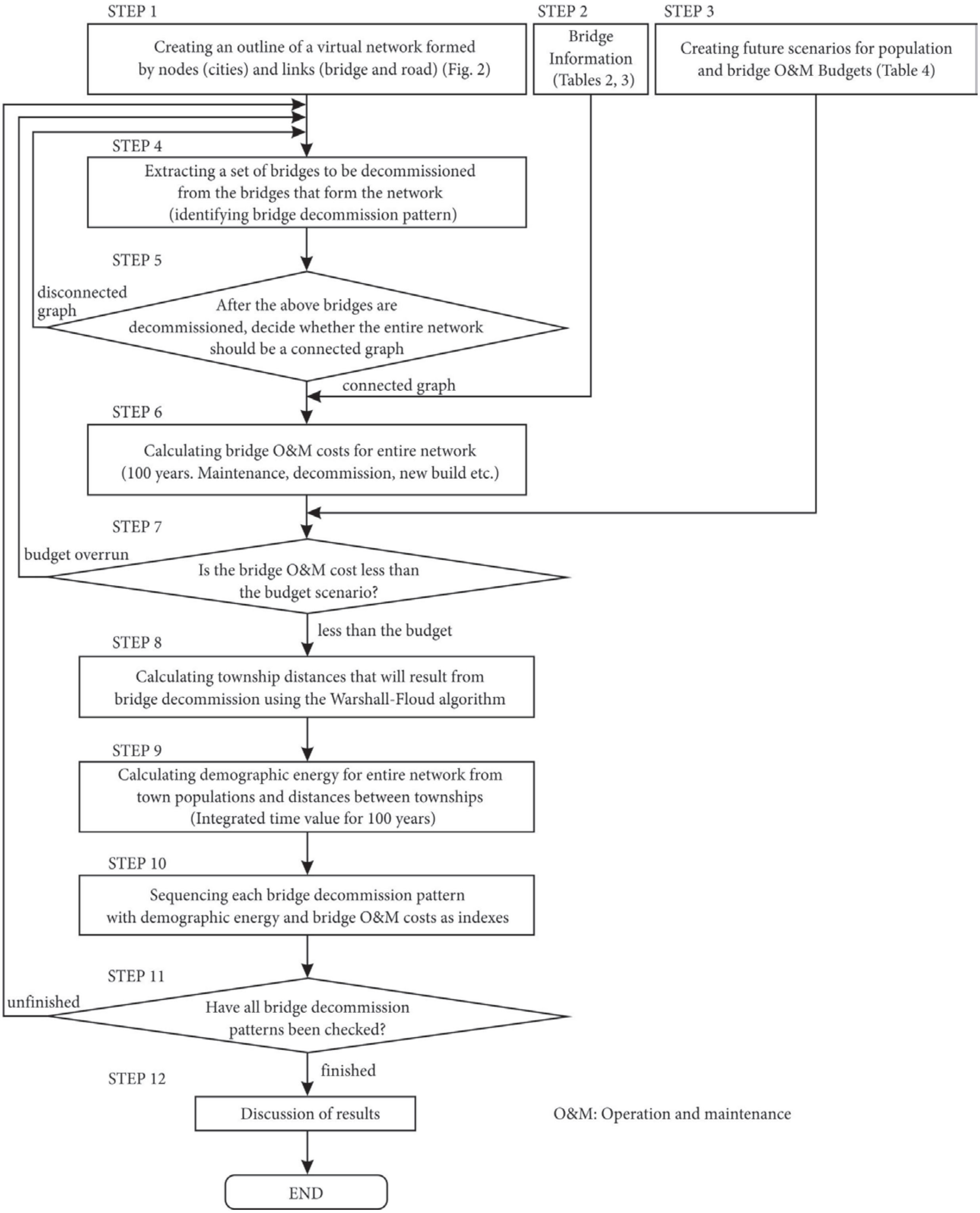
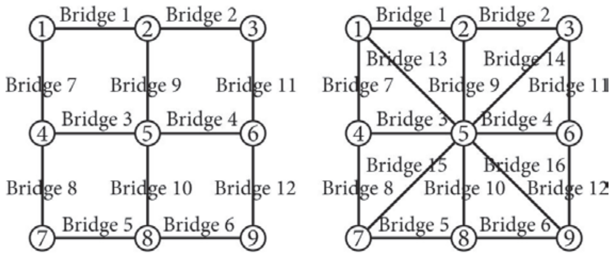


Fig. 1. Research flowchart

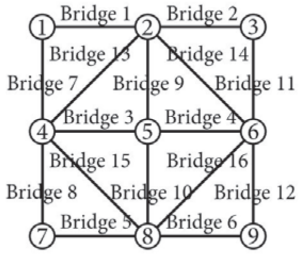
(horizontal and vertical links) that comprise basic networks. Nodes contain the population of a town. The population is assumed to decrease at a constant rate based on a given scenario. Links are comprised of bridges and roads, while the focus is placed on bridges for the purpose of this study. A simulation involving repairs, decommissions, and new installations is performed for a period of 100 years.

STEP 2: Bridge information.

The maximum number of bridges for a virtual network is assumed to be 16. The Bridge information and the construction costs are shown in Tables 2 and 3, respectively, based on a literature review (Society for Road Structures Conservation, Road Management Technology Center ed. 2008; Ohshima 2009) and previous research



(1) Basic network (2) Radial network



(Length of link)
Horizontal and vertical link: 1
Diagonal link: 1.4

(3) Ring network

Fig. 2. Outline of virtual network

(Kita, Chikata 2010). There are two categories of maintenance and repair work for each bridge. These bridges are imaginary and do not actually exist.

Tables 2 and 3 are prepared based on the concept of preventive maintenance of bridges. This concept is intended for extending the lifespan of bridges by implementing repairs and improvements on deteriorations, and maintenance of asset values before their performance levels reach management limits. A conceptual diagram depicting the deterioration and lifespan of a bridge is shown in Fig. 3. Repair work is implemented periodically to each repair segment at fixed intervals, for the purpose of this study. This continues until a bridge reaches a lifespan of 100 years.

STEP 3: Creating scenarios for reduced populations and the operation and maintenance budgets for bridges.

Scenarios for the transitions of population decline and budget decline over the 100-year period are prepared, as shown in Table 4.

Table 2. Tentative bridge information (example: Bridges 1–5)

Bridge number	Bridge information		Maintenance and Repair	
Bridge 1	Type of bridge	Concrete	Construction category 1	Repair work on old beams
	Length	20 m	Repair cycle 1	30 years
	Width	6 m	Construction category 2	Repair of salt damaged beams
	Area	120 m^2	Repair cycle 2	15 years
	Current age	5 years		
Bridge 2	Type of bridge	Steel	Construction category 1	Beam painting
	Length	25 m	Repair cycle 1	20 years
	Width	6 m	Construction category 2	Repair for aged flooring
	Area	150 m^2	Repair cycle 2	40 years
	Current age	70 years		
Bridge 3	Type of bridge	Concrete	Construction category 1	Repair work on old beams
	Length	45 m	Repair cycle 1	30 years
	Width	9 m	Construction category 2	Repair of salt damaged beams
	Area	405 m^2	Repair cycle 2	15 years
	Current age	50 years		
Bridge 4	Type of bridge	Steel	Construction category 1	Beam painting
	Length	30 m	Repair cycle 1	20 years
	Width	8 m	Construction category 2	Repair for aged flooring
	Area	240 m^2	Repair cycle 2	40 years
	Current age	30 years		
Bridge 5	Type of bridge	Concrete	Construction category 1	Repair work on old beams
	Length	15 m	Repair cycle 1	30 years
	Width	7 m	Construction category 2	Repair of neutralization on beams
	Area	105 m^2	Repair cycle 2	40 years
	Current age	60 years		

Table 3. Tentative construction cost of bridge (example: Bridges 1–5)

Bridge number	Construction type	Construction specifications	Amount (estimation)
Bridge 1	Repair work on old beams	Unit price/area	40/m^2 Eur
		Construction cost	4839 Eur
	Repair of salt damaged beams	Unit price/painting/area	282/m^2 Eur
		Unit price/scaffolding (hanging)	36/m^2 Eur
		Scaffolding area = (width + 1 m) × length	140 m^2
		Construction cost	38 952 Eur
	Decommissioning	Unit price/decommission/area	806/m^2 Eur
		Construction cost	96 774 Eur
	New build	Unit price/new build/area	4032/m^2 Eur
		Construction cost	483 871 Eur
Bridge 2	Beam painting	Unit price/painting (type three cleaning)	24/m^2 Eur
		Paint area = 3.1 × bridge area	465 m^2
		Unit price/scaffolding (hanging)	36/m^2 Eur
		Scaffolding area = (width + 1 m) × length	175 m^2
		Construction cost	17 601 Eur
	Repair for aged flooring	Unit price/carbon fiber adhesive	403/m^2 Eur
		Unit price/scaffolding (hanging)	36/m^2 Eur
		Scaffolding area = (width + 1 m) × length	175 m^2
		Construction cost	66 835 Eur
	Decommissioning	Unit price/decommission/area	806/m^2 Eur
		Construction cost	120 968 Eur
	New build	Unit price/new build/area	4032/m^2 Eur
		Construction cost	604 839 Eur
Bridge 3	Repair work on old beams	Unit price/area	40/m^2 Eur
		Construction cost	16 331 Eur
	Repair of salt damaged beams	Unit price/painting/area	282/m^2 Eur
		Unit price/scaffolding (hanging)	36/m^2 Eur
		Scaffolding area = (width + 1 m) × length	450 m^2
		Construction cost	130 645 Eur
	Decommissioning	Unit price/decommission/area	806/m^2 Eur
		Construction cost	326 613 Eur
	New build	Unit price/new build/area	4 032/m^2 Eur
		Construction cost	1 633 065 Eur
Bridge 4	Beam painting	Unit price/painting (type three cleaning)	24/m^2 Eur
		Paint area = 3.1 × bridge area	744 m^2
		Unit price/scaffolding (hanging)	36/m^2 Eur
		Scaffolding area = (width + 1 m) × length	270 m^2
		Construction cost	27 798 Eur
	Repair for aged flooring	Unit price/carbon fiber adhesive	403/m^2 Eur
		Unit price/scaffolding (hanging)	36/m^2 Eur
		Scaffolding area = (width + 1 m) × length	270 m^2
		Construction cost	106 573 Eur
	Decommissioning	Unit price/decommission/area	806/m^2 Eur
		Construction cost	193 548 Eur
	New build	Unit price/new build/area	4032/m^2 Eur
		Construction cost	967 742 Eur
Bridge 5	Repair work on old beams	Unit price/area	40/m^2 Eur
		Construction cost	4234 Eur
	Repair of neutralization on beams	Unit price/area (2-layer carbon fiber adhesion)	403/m^2 Eur
		Unit price/scaffolding (hanging)	36/m^2 Eur
		Scaffolding area = (width + 1 m) × length	120 m^2
		Construction cost	46 694 Eur
	Decommissioning	Unit price/decommission/area	806/m^2 Eur
		Construction cost	84 677 Eur
	New build	Unit price/new build/area	4032/m^2 Eur
		Construction cost	423 387 Eur

The model for the decrease in the population is calculated as follows. And the initial values of population for each town are set for the purpose of this study, in the manner shown in Table 5.

(Scenario 1) $$P_{it} = -\frac{P_{i0}}{300}t + P_{i0}, \qquad (1)$$

(Scenario 2) $$P_{it} = -\frac{P_{i0}}{200}t + P_{i0}, \qquad (2)$$

where P – a town's population; i - town number (i = 1, 2, …, 9); t – the number of years (t = 1, 2,…, 100); P_{i0} – the initial population.

There are two future scenarios which are related to the operation and maintenance costs of bridges. They are prepared using the average annual cost for maintaining all the existing 12 bridges or 16 bridges for 100 years as the initial value. The Scenario 1 has the value decreasing two-thirds, and the Scenario 2 has the value decreasing to one-half in 100 years. A primary monotone decreasing function is used to estimate the cost for each year, which is then used to derive the total cost for the 100-year. The total cost is then used as the budget constraint for conducting simulations.

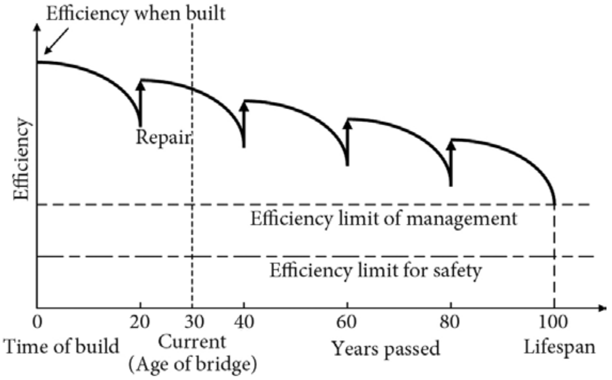


Fig. 3. Outline of bridge lifespan (when bridges last for 100 years) Data source: reference (Ohshima 2009) (This figure is touched up from the original figure by authors)

Table 4. The scenarios of population and bridge operation and maintenance budget

	Population	Bridge operation and maintenance budget
Scenario 1	decrease to 2/3 after 100 years	decrease to 2/3 after 100 years
Scenario 2	decrease to 1/2 after 100 years	decrease to 1/2 after 100 years

Table 5. Tentative population of each town

Town number	Initial population value, people
1	5000
2	7000
3	20 000
4	1000
5	20 000
6	15 000
7	10 000
8	3000
9	2000

STEP 4: Extracting a set of bridges to be decommissioned from those in the network (identifying bridge decommissioning patterns).

Bridges that are decommissioned are derived as a subset of all bridges.

STEP 5: Deciding whether to make the network a connected graph.

This study decided on graph connectivity to prevent having towns that could not be reached from other towns following bridge decommissioning. If all results from calculating

$$A + A^2 + \ldots + A^{N-1}, \qquad (3)$$

for the adjacency matrix A of the undirected graph are positive, then the network is a connected graph, where N – the number of vertices (Langville, Meyer 2006; Naito 2011).

STEP 6: Calculating the operation and maintenance costs for bridges throughout the network

In STEP 5, this study established that the network is a connected graph. If this study considers the lifespan of a bridge to be 100 years, then it is possible to predict the remaining life of a bridge. The decision to decommission a bridge and not to rebuild it is only taken at the end of life. The decision to extend the life of a bridge means that if the bridge is decommissioned upon end of life, and immediately a new bridge is constructed. By repeating this process, all bridge lifespans will expire in 100 years and the bridges will form the aforementioned network as a connected graph. The operation and maintenance costs (i.e., maintenance, decommissioning, and new construction) for bridges during this period are calculated based on Tables 2 and 3.

$$C_k = \sum_{t=1}^{100} \frac{C_{kt}}{\left(1+r\right)^t}, \qquad (4)$$

where t – the number of years passed; k – the bridge decommission pattern (k = 1, 2, …, number of bridge subsets); C_{kt} – the operation and maintenance costs t years after bridge decommission pattern k; C_k – the operation and maintenance costs 100 years after bridge decommission pattern k (present value); r – the social discount rate (set as 1% based on the long-term prime rate as of August 2015).

STEP 7: Determining whether operation and maintenance costs can be managed within the budget.

An evaluation is conducted to determine whether operation and maintenance costs derived in STEP 6 could be managed within the budget decline scenario in STEP 3.

STEP 8: Calculating township distances that will result from bridge decommission using the Warshall-Floyd algorithm.

The distances between the towns will change following the decommissioning of certain bridges. Using the Warshall–Floyd algorithm, this study successively calculates the shortest distances between two towns whenever a bridge is decommissioned (Floyd 1962; Pradhan 2013; Wang 2014; Warshall 1962).

STEP 9: Calculating the demographic energy for the overall network from town populations and distances.

This study evaluates the efficiency of a network based on demographic energy. Demographic energy is a concept introduced by Stewart, a proponent of social physics (Nogami, Sugiura 1986; Stewart 1948). The concept is based on Newton's theory of universal gravitation, and models the interaction of population groups. Stewart validated this theory by using actual data to verify that the distribution of demographic energy within the United States corresponded relatively well with the economic data comprising of such aspects as revenues in each state. This theory has since then been applied in a variety of fields such as economy and city planning (Anderson 2011; Bergstrand, Egger 2011; Gray, Sen 1983; Smith 1975).

Applying this theory to a virtual network prepared for the purpose of this study makes it possible to express the demographic force F that is acting between two cities, as well as the demographic energy for the entire network E, in the following manner:

$$F_{kt} = G\frac{P_{it}P_{jt}}{d_{ijkt}^2}, \tag{5}$$

$$E_{kt} = \sum_{i=1}^{9}\sum_{j=1}^{9} G\frac{P_{it}P_{jt}}{d_{ijkt}}, \tag{6}$$

where F – the demographic force; E – the demographic energy for entire network; P – the town's population; d –the distance between two towns; G – can arbitrary parameter; i – a town number ($i = 1, 2, \ldots, 9$); j – a town number ($j = 1, 2, \ldots, 9$); k – a bridge decommission pattern ($k = 1, 2, \ldots$, number of bridge subsets); t – the number of years passed ($t = 1, 2, \ldots, 100$); t_{km} – the year a bridge is decommissioned; m – the order of decommission for each bridge decommission pattern ($m = 1, 2, \ldots$, number of decommissioned bridges); A_k – an integrated time value of the demographic energy.

The arbitrary parameter G is considered as a constant for comparing E_{kt}. In this instance, G is fixed to 1. E_{kt} is the demographic energy at a specific point in time. A simulation is conducted for a period of 100 years in this study, but the value of E_{kt} changes throughout this period. For the purpose of this study, A_k (hereinafter referred to as "demographic energy") is used as an integrated time value of demographic energy, which is an index that represents the scale of the demographic energy over the period of 100 years. A_k represents the shaded area depicted in Fig. 4.

STEP 10: Sequencing each bridge decommission pattern using demographic energy and bridge operation and maintenance costs as indices.

$$A_k = \int_0^{100} E_{kt}dt = \int_0^{t_{k1}} E_{kt}dt + \int_{t_{k1}}^{t_{k2}} E_{kt}dt + \int_{t_{k2}}^{t_{k3}} E_{kt}dt + \int_{t_{k3}}^{100} E_{kt}dt. \tag{7}$$

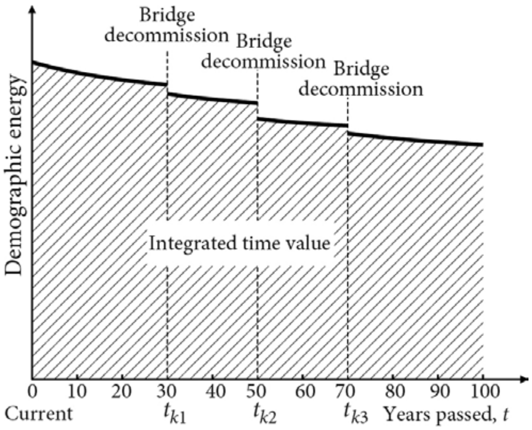


Fig. 4. Bridge decommission and demographic energy

In this step, this study implements the sequencing of each bridge decommission pattern using the indices A_k (integrated time value for demographic energy), C_k (operation and maintenance costs), A_k/C_k (demographic energy per unit cost), and so on.

STEP 11: Determining whether or not all bridge decommissioning patterns have been verified.

Determining whether or not all bridge decommissioning patterns have been verified according to the procedures of STEP 4 to STEP 10.

STEP 12: Discussion of results.

Here, discussion of results is conducted.

6. Research findings

The research findings are shown below.

7. Discussion of results

This study was conducted to verify the impact of bridge decommissioning, through simulations, by establishing virtual networks comprising of links (roads that include bridges). Interesting results were observed in the simulations.

Table 6 represents the characteristics of three network patterns. Although radial and ring networks have longer link lengths than basic networks, the probability of the connected graph being sustained after a bridge is decommissioned is higher. In particular, 28.2% of all bridge decommissioning patterns showed in connected graphs in the case of radial networks, which comprised the largest proportion among the three network types. In this instance, although the link lengths are similar for both radial and ring networks, radial networks have a higher probability of resulting in connected graphs. The pattern of roads concentrated in a town center is similar to the pattern observed during the initial phase of city development, as

Table 6. Length of link and connectivity of each network type

Type of network	Length of link	Among all patterns for bridge decommissioning, the patterns that make up the connected graph and their ratio
(1) Basic network	12.0	431 out of 4096 patterns (10.5%)
(2) Radial network	17.6	18 462 out of 65 536 patterns (28.2%)
(3) Ring network	17.6	14 864 out of 65 536 patterns (22.7%)

represented by a radial network. In addition, the results of this study indicate that this network type featured superior redundancy for detours. However, radial networks are prone to the occurrence of traffic congestions, as roads are concentrated in a single town center. For this reason, ring networks are being established in the environs of Tokyo in Japan in recent years, in addition to such radial networks. Table 7 depicts the demographic energy A_k of Scenario 1 in the radial network, in the order of sequence. The nation and the municipality would like to maintain as high a demographic energy as possible. However, if doing so means that the operation and maintenance costs continually exceed tax

Table 7. Sequence of demographic energy A_k (Radial network, Scenario 1, Top 16)

Sequence	Demographic energy A_k	Bridge decommission pattern	Operation and maintenance cost C_k (million Eur)
1	1 438.12	{Φ}	18.83
2	1 437.52	{8}	17.78
3	1 437.33	{1}	18.19
4	1 437.14	{7}	17.97
5	1 436.87	{7,8}	17.38
6	1 436.73	{1,8}	17.60
7	1 436.35	{1,7}	17.78
8	1 436.08	{1,7,8}	17.19
9	1 434.85	{6}	17.13
10	1 434.43	{13}	17.81
11	1 434.25	{6,8}	16.54
12	1 434.06	{1,6}	16.94
13	1 433.87	{6,7}	16.72
14	1 433.68	{8,13}	17.21
15	1 433.60	{6,7,8}	16.13
16	1 433.46	{1,6,8}	16.35

Note: The budget limit: Radial network, Scenario 1 (16.68 million Eur)

Table 8. Demographic energy A_k, Operation and maintenance cost C_k of each pattern of bridge decommission (Radial network, Scenario 1 and 2)

Case	Budget scenario	Bridge decommission pattern	Demographic energy A_k	Operation & maintenance cost C_k (million Eur)
(a) A case that is within the budget, where the demographic energy A_k is maximum	Scenario 1	{6,8}	1 434.25	16.54
	Scenario 2	{6,7,8,15}	1 182.47	15.26
(b) A case where a maximum amount of the budget is used up	Scenario 1	{4,5,7,14}	1 348.54	16.68
	Scenario 2	{2,3,5,7,11}	1 126.66	15.30
(c) A case where (demographic energy A_k/ Operation and maintenance C_k) is maximum	Scenario 1	{3,8,9,11,12,13,15,16}	1 346.41	9.43
	Scenario 2	{3,8,9,11,12,13,15,16}	1 127.33	9.43

Table 9. Bridge decommission pattern of each network type

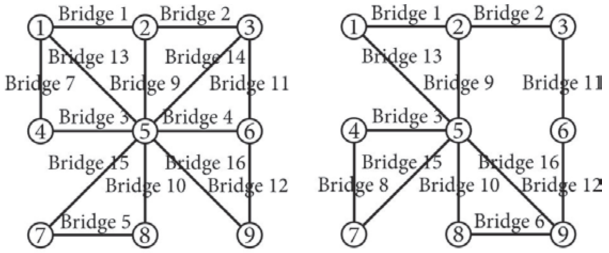
Type of network	A case that is within the budget, where the demographic energy A_k is maximum		A case where a maximum amount of the budget is used up		A case where (demographic energy A_k / Operation and maintenance cost C_k is maximum	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
(1) Basic network	{6,8}	{6,7,11}	{1,4,5,10}	{6,7,11}	{3,8,9,12}	{3,8,9,12}
(2) Radial network	{6,8}	{6,7,8,15}	{4,5,7,14}	{2,3,5,7,11}	{3,8,9,11,12,13,15,16}	{3,8,9,11,12,13,15,16}
(3) Ring network	{7,8,15}	{3,8,13,15}	{4,5,7,14}	{1,2,13,14,16}	{3,8,9,12,13,14,15,16}	{3,8,9,11,12,13,15,16}

revenue, some bridges cannot be maintained. In this case, decisions will be based on the demographic energy index. In other words, based on the funds available for the operation and maintenance of bridges, the best option will be the bridge decommission pattern that maximizes demographic energy. Other possible indices include the operation and maintenance costs of bridges and the demographic energy per unit cost of bridges. These indices can also be used by the nation and municipalities to aid them in their decision-making. The budget constraint for Scenario 1 in this table is 16,68 million Eur. The pattern that can be managed within the budget, which involves the decommissioning of bridges with the maximum demographic energy, is {6,8}, which is ranked 11th. The shaded areas in the table represent bridge decommissioning patterns that can be managed within the budget. Those ranked 12th to 14th have a lower demographic energy than {6,8}, but involve higher costs. It is evident from Table 7 that increasing the cost does not necessarily result in serving larger demographic energy.

Among the cases listed in Table 8, case (a) with the maximum demographic energy A_k can be managed within the budget. Case (a) represents the case that can preserve the maximum amount of demographic energy with limited cost. As it is evident from Fig. 5a, the redundancy of routes are secured relatively well in case (a). Case (b), with the maximum amount of budget expended, creates a heavier cost burden than case (a), but results in inferior performance in terms of demographic energy and redundancy (Fig. 5b). Case (c), with the maximum value of the ratio of demographic energy A_k to the operation and maintenance costs of bridges C_k is the case with the best cost effectiveness. However, in this instance, the cost is suppressed because of increasing the efficiency, but the redundancy of the network is lost (Fig. 5c), resulting in a greater disadvantage in terms of securing routes in an event of disaster.

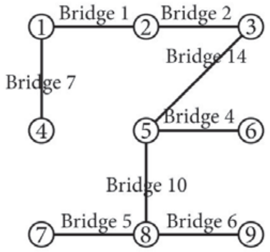
Table 9 and Fig. 6 depict cases involving bridge decommissioning, categorized according to network modes. These are all results from simulations performed using the initial values of demographics featured in Table 5. The simulation results naturally change when the population distribution changes. The proposed methodology of the study is a methodology that is capable of accommodating various network modes and population distributions.

A virtual network and virtual bridge data were used as source data in this instance, but these can be replaced with actual data to prepare an index that can be used to respond to operation and management issues for real bridges.



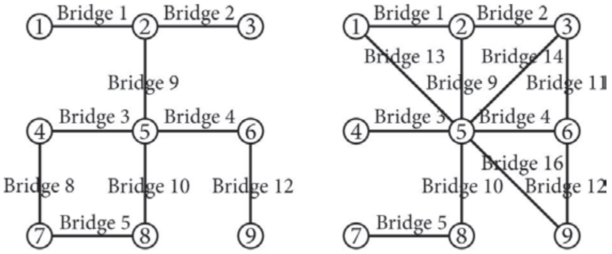
(a) A case that is within the buget, where the demographic energy (A_k) is maximum

(b) A case where a maximum amount of the buget is used up



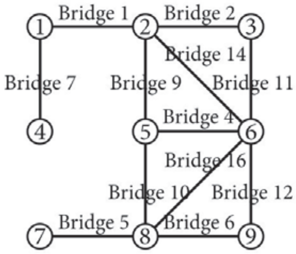
(c) A case where (demographic energy (A_k)/Operation and maintenance cost (C_k) is maximum

Fig. 5. Bridge decommission example (Radial network, Scenario 1)



(1) Basic network

(2) Radial network



(3) Ring network

Fig. 6. Bridge decommission example (a case that is within the budget, where the demographic energy (A_k) is maximum, Scenario 2)

8. Conclusion

1. The main contribution of our paper is that the proposed methodology is available and capable to be used to identify whether or not an existing bridge that has reached the end of its service life should be decommissioned based on cost and convenience.

2. The proposed triage methodology for bridges uses a concept of demographic energy which is calculated for the overall network from town's populations, township distances and network connectivity. The triage methodology can also be applied to other countries which may face a decreasing population and/or rising debt in the future.

3. The problem of how to deal with the computational loads hereafter still remains since increased computational demand arises when the peak number becomes relatively large. Here, the branch and bound method could be employed to increase search efficiency, in order to reduce the computational loads required for determining connectivity.

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