Sixth International Conference on Durability of Concrete Structures **Paper Number DSM12**
18 - 20 July 2018
University of Leeds, Leeds, West Yorkshire, LS2 9JT, United Kingdom

Social Dimensions in Sustainability Evaluation of Deteriorating Reinforced Concrete Bridges

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ABSTRACT

Structural sustainability requires that structural engineering activities should find ways to design and maintain structures that perform as required during their life-cycle considering intergenerational needs. Massive attention has been paid to the economic and environmental evaluation of structures. However, being a completely different discipline from structural engineering, the social dimensions associated with structures were rarely considered in previous studies due to the difficulty in determination and quantification, unavoidable subjectivity and controversy, as well as the lack of historical data. This paper identifies the social impacts induced by engineering activities associated with the deterioration of reinforced concrete structures, and proposes corresponding computational approaches from the structural engineering viewpoint. Utility theory is used herein to measure, normalize and combine different social attributes with consideration of the risk attitudes of decision makers. A case study is performed on a deteriorating reinforced concrete bridge to compare the social performances of different maintenance strategies based on the associated multi-attribute social utility values.

Keywords: Social dimensions; sustainability; utility theory; reinforced concrete structures.

1.0 INTRODUCTION

Structural sustainability requires that our engineering activities should find ways to meet current needs without destroying the opportunities for the development of the future generations (Kestner, Goupil, and Lorenz, 2010). Sustainability is supported by three pillars, i.e. economy, environment and society, as claimed in the 2005 World Summit on Social Development (Bocchini *et al.*, 2014; Ali, Aslam, and Mirza, 2016). With respect to the social dimensions, a generally accepted scope of social impacts includes all the social and cultural consequences to human populations of any public or private actions that alter the ways in which people live, work, play, relate to one another, organize to meet their needs, and generally cope as members of society (Vanclay, 2002; Burdge *et al.*, 2003). In this context, various indicators and variables for social impact assessment (SIA) have been proposed, and some representative categories are presented in Table 1. SIA has been used to identify the potential social changes induced by government policies, but its implementation on structural design and decision making is rare.

Compared with the extensive studies on economic and environmental impacts of engineering activities, the social dimensions and SIA were scarcely considered or applied in the past. The major reason is that SIA and structural engineering are completely different disciplines, and most structural engineers are not familiar with the measurement of social impacts. Other reasons mainly include the lack of experience and historical data, difficulty in determination and quantification, subjectivity and controversies in measurements (Arditi and Messiha, 1999), correlations between different social dimensions (Burdge *et al.*, 2003), as well as ambiguity in terms and methodologies (Parris, and Kates, 2003).

To facilitate the implementation of SIA in structural design and evaluation, this paper proposes social impact indicators that contain structural engineering parameters, such as failure probability and reliability. Utility theory can be used to measure, combine and consistently compare utility values associate with different social attributes, and the utility values usually reflect the preferences and desirability of decision makers (Sabatino, Frangopol, and Dong, 2015 & 2016; Frangopol, and Soliman, 2016). Hence utility theory is applied in this paper to

Table 1. Social impact categories

Authors	Social Impact Categories
Interorganizational Committee on Guidelines and Principles, 1995	Population characteristics; Community and institutional structures; Political and social resources; Individual and family changes; Community resources.
Vanclay, 1999	People's way of life; Culture; Community; Political system; Environment; Health and well-being; Personal and property rights; Fears and aspirations.
Lockie *et al.*, 2008	Health and social well-being; Liveability; Economic impacts and material well-being; Cultural impacts; Family and Community Impacts; Institutional, legal, political and equity impacts; Gender relations.
Juslèn, 1995	'Standard' social impacts (noise, pollution, *et al.*); Psychosocial impacts; Anticipatory fear; Impacts of carrying out the assessment; Impacts on state and private services; impacts on mobility.
Taylor *et al.*, 1990	Lifestyles; Attitudes; Beliefs and values; Social organization.

normalize the social attributes, so as to eliminate the inconsistency in units and scopes of different social dimensions.

The main novelty of this paper is the identification and quantification of social dimensions considering structural engineering's need. The computational formulas for selected social impacts are provided, and the social impacts are divided into social benefits and social burdens considering whether they have positive or negative impacts on the society. After a review of utility theory, the utility functions associated with social benefits and social burdens are presented given the risk attitudes of decision-makers. In the case study, the multi-attribute social utility values associated with different maintenance strategies of a deteriorating reinforced concrete (RC) bridge are compared to obtain the maintenance strategy that has the best social performances.

2.0 SOCIAL IMPACTS OF STRUCTURES

The structural engineering activities-related social impacts considered herein are divided into personal-level and social-level impacts, as shown in Figure 1. The personal-level impacts are related to the physical, psychological, and economical conditions of people; and the social-level impacts refer to the human settlements, social-economic development, as well as social facilities.

2.1 Personal-level Impacts

Physical Impacts

People's health and well-being is used herein to evaluate the physical impacts of engineering activities, which can be quantified by the health damages/disabilities and fatalities. Weidema (2006) employed the damage indicator Years of Life Lost (YLL) to measure the changes in expected length of life, and healthy Years Lost due to Disability (YLD) to measure the changes in health conditions. The YLD can be integrated to the YLL using a common unit of Disability Adjusted Life Years (DALY). Padgett *et al.* (2010) computed the fatalities under hazards on the basis of the damage state of bridges and the fatality numbers assoicated with specific states. In the fatality estimation performed by Zhu & Frangopol (2012), traffic conditions and detour length are considered. This method is used in this paper to measure the pysical impacts of deteriorating structures, as shown in Eq. 1 (Sabatino, Frangopol, and Dong, 2015).

$$FT(t) = P_f(t)\left(\frac{L}{f_d}+1\right)\left[O_r\left(1-\frac{TT_p}{100}\right)+\frac{TT_p}{100}\right] \quad \textbf{(1)}$$

where FT(t) is the number of expected fatalities at time t; $P_f(t)$ is the failure probability of the deteriorating bridge at time t; L is the length of the bridge (m); f_d is the safe following distance during driving (m); O_r is the occupancy rate for non-truck vehicles; and TT_p is the percentage of average daily traffic that is truck (%).

Psychological Impacts

Public trust in government and social institutes can be affected by a variety of factors including administrative capacities, achievements and scandals (Chanley, Rudolph, and Rahn, 2000; Christensen and Lægreid, 2005). The trust degree is also region-specific and culture-specific. The trust degree (TD) model purposed in this paper relates the reliability state of the bridge to the administrative capacities of the government. It reckons that the degraded conditions of civil infrastructure and the rise of associated accidents can erode the public trust in local government and social institutes, while active responses to the degraded structures such as maintenances and repair can rebuild the trust. The public trust associated with bridge structures mainly depends on the states of the bridges. Therefore, a simplified trust degree (TD) model is built based on the current and target reliability indexes, as shown in Eq. 2.

$$TD(t) = \frac{\beta(t)}{\beta_{target}} - 1 \quad (2)$$

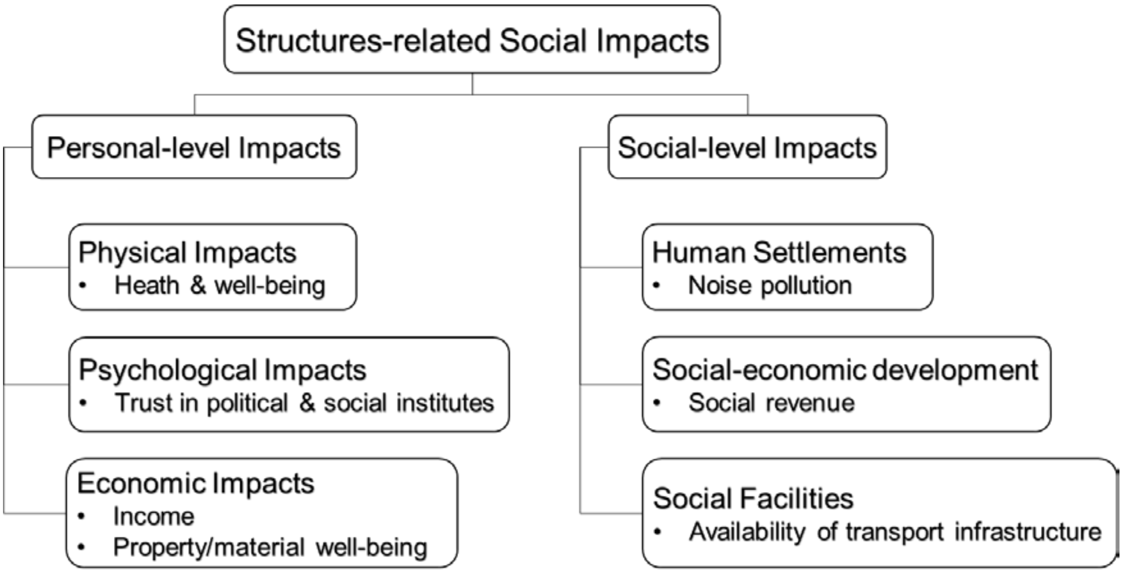

Fig. 1. Social impact indicators related to structures

where TD(t) is the public trust degree at time t; β(t) is the structural system reliability index at time t; and β_{target} is the target reliability index of the structure.

Economic Impacts

Social impacts induced by deteriorating bridge structures can also occur in personal economic condition, including incomes and property/material well-being. Bridges require maintenances in response to degradation, otherwise structural failure will happen in the near future. Either way, bridge structures can face function loss and interfere with bridge users' daily life. The associated income loss (IL) is caused by the extra time spent on detours, which can be computed by Eq. 3 (Frangopol, 2011; Dong, Frangopol, and Saydam, 2013; Cho *et al.*, 2004). The property loss (PL) herein refers to the extra vehicle operation cost due to detour, as expressed by Eq. 4 (Dong, Frangopol, and Saydam, 2013; Cho *et al.*, 2004).

$$IL=\left[c_{w,car}O_r\left(1-\frac{TT_p}{100}\right)+c_{w,truck}\frac{TT_p}{100}\right]\frac{D_l A d_t}{S}(1+r)^t \qquad (3)$$

$$PL=\left[c_{r,car}\left(1-\frac{TT_p}{100}\right)+c_{r,truck}\frac{TT_p}{100}\right]D_l A d_t(1+r)^t \qquad (4)$$

where IL and PL are the income loss and property loss due to detour, respectively (CNY); $c_{w,car}$ and $c_{w,truck}$ are the wage of car drivers and truck drivers, respectively (CNY/h); $c_{r,car}$ and $c_{r,truck}$ are the operation cost of cars and trucks, respectively (CNY/km); A is the average daily traffic (ADT); D_l is the detour length (km); d_t is the downtime (days); S is the average detour speed (km/h); r is the monetary discount rate, assumed 2% in this paper; and t is the time.

2.2 Social-level Impacts

Human Settlements

Whether a community is liveable largely depends on its human settlement environment. Noise pollution (NP) is the major harmful impact derived from engineering activities that can affect the social living environment. When a measuring point receives noises that exceed a certain limitation, it means this region or community is polluted by noises. NP can disrupt people's conversation, contemplation, rest and sleep, or even damage people's audition (Stansfeld and Matheson, 2003). The noise factor (NF/dB) is used to measure the level of noise. This paper presents a simplified model to evaluate the level of NP: suppose that NF exceeds the limited noise factor (NFL) during time period ∆t, as indicated in Fig. 2, the associated NP equals to the ratio between area A' and area A. In addition, different regions can have different noise limitations. For example, educational institutions, hospitals and sanatoriums usually have stricter noise limitations, while commercial districts, traffic stations, factories have relatively loose restrictions. Considering all the places affected, the simplified NP model of engineering activities is proposed as:

$$NP=\sum_i\left(\frac{\int_{\Delta t_i} NF_i(t)dt}{NFL_i\cdot\Delta t_i}-1\right) \qquad (5)$$

where NP is the noise pollution; $NF_i(t)$ is the noise factor of the ith affected region at time t (dB); NFL is the noise factor limitation (dB) of the ith affected region; Δt_i is the time period of noise pollution of the ith affected region.

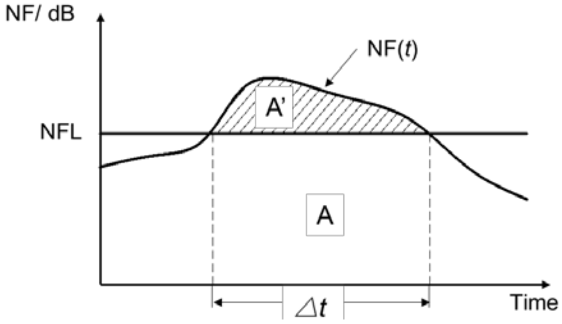

Fig. 2. Schematic diagram of noise pollutions

Social-economic development
The deterioration and failure of infrastructure, especially the vital nodes in transportation networks such as bridges and tunnels, can reduce the total social revenues (SR) from agriculture, industry, building industry, transportation and post, commerce, tourism, and other sources. Consider a deteriorating bridge between an island and the mainland as an example: if it fails, the agricultural or industrial products from the island that need to be transported immediately will face cargo loss; the poor transportation condition can also reduce the revenues of tourism, shopping malls, or other recreation businesses on the island. In general, the social-economic impacts of a deteriorating bridge are related to the industries whose supply and marketing depend on this bridge, which can be expressed by:

$$\Delta SR = \Delta R_A + \Delta R_I + \Delta R_T + \Delta R_R + \Delta R_O \tag{6}$$

where ΔSR is the social revenue loss induced by deterioration of failure of bridges (CNY); ΔR_A, ΔR_I, ΔR_T, ΔR_R and ΔR_O are the decreases of revenues in agricultural, industrial, transportation, recreation and other areas (CNY), respectively. The revenue loss associated with a certain deteriorating bridge can be estimated based on previous experience, historical data or field research of the region.

Social facilities
Social facilities are the structures designed, built or installed to provide space for living or interaction among persons in a community, among which the transport infrastructure such as bridges are important ones. The availability of transport infrastructure (ATI) is used in this paper to describe the effects of deteriorating or failed bridges on the entire social transportation network (Cloquell-Ballester *et al.*, 2006), as

$$ATI_i = A_{road} \cdot K_{road} \tag{7}$$

where ATI_i is the availability of transport infrastructure; A_{road} is the ordinal scale [0,9] measuring the accessibility from the community to roads, where 0 means not available, and 9 means totally accessible; and K_{road} is the weighed sum of major roads length and minor roads length (km).

3.0 UTILITY ASSESSMENT ON SOCIAL DIMENSIONS

Utility theory is used herein to describe the relative desirability of bridge maintenance strategies to decision makers considering their risk attitudes (Sabatino, Frangopol, and Dong, 2016). Utility values are assigned to each attributes, and then combined to a single utility value that represents the decision-makers' attitude towards the overall social impacts of the bridge maintenance strategy.

3.1 Utility Assignment for Single Social Attribute

The attributes associated with social impacts can be divided into two types: (a) social benefit, whose desirability increases when its attribute value increases, and (b) social burden, whose desirability decreases when its attribute value increases. Among the social impacts discussed in this paper, the trust degree (TD) and availability of transport infrastructure (ATI) are social benefits, while the fatalities (FT), income loss (IL), property loss (PL), noise pollution (NP) and social revenue loss (ΔSR) are social burdens. The utility functions for social benefits and social burdens are (Ang, and Tang, 1984):

$$u_{bf} = \frac{1}{1-\exp[-\gamma]}\left(1-\exp\left[-\gamma\frac{a-a_{\min}}{a_{\max}-a_{\min}}\right]\right) \tag{8}$$

$$u_{bd} = \frac{1}{1-\exp[-\gamma]}\left(1-\exp\left[-\gamma\frac{a_{\max}-a}{a_{\max}-a_{\min}}\right]\right) \tag{9}$$

where u_{bf} and u_{bd} are the utility functions for social benefit and social burden, respectively; γ is the risk attitude of the decision makers: $\gamma > 0$ means risk aversion, $\gamma < 0$ shows risk acceptance, and $\gamma = 0$ indicates risk neutral attitude; a is the expected attribute value; a_{min} is the minimum attribute value; and a_{max} is the maximum attribute value.

3.2 Multi-attribute Utility Assessment for Social Impacts

The additive formulation is employed herein to combine the utility values of various social attributes into a single utility value that represents the overall social performance, and the multi-attribute utility value equals to the weighted sum of the utility values of all investigated attributes. Hence, the multi-attribute utility function of the overall social performance is computed as (Dong, Frangopol, and Sabatino, 2015):

$$u_{social} = \sum_i w_i u_i \tag{10}$$

where u_{social} is the multi-attribute utility function of overall social performance; w_i is the weighting factor for the ith social attribute, and $\sum_i w_i = 1$; and u_i is the utility value associated with the ith social attributes, including TD, ATI, FT, IL, PL, NP and △SR.

After combining the utility values of all investigated social attributes, a single utility value can be used to depict and compare the relative desirability towards the social dimensions of different maintenance strategies. In the following section, a deteriorating RC bridge will be studied to compare the social utility values of two types of maintenance strategies.

4.0 CASE STUDY

The RC highway bridge that connects the Island J with the mainland is taken as an example in this paper, as shown in Fig. 3. The length of the bridge L=8 km, and width W=26 m. The bridge deck is under the effect of marine atmosphere, deicing salt and surface abrasion. As stated above, the ultimate purpose of this example is to compare the social utility values among different maintenance strategies, so the reliability degradation process of the bridge deck is simplified to a hypothetic three-stage polyline that includes the initiation, propagation and deterioration stage, as shown in Fig. 4. Initial reliability index β_0= 4.2 and target reliability index β_{target}= 3.7. The designed service life is 75 years. Without routine maintenances, the bridge deck will be affected by steel corrosion and concrete cracking and it is assumed to fail 22 years after the construction. The initiation stage is assumed to be 12 years, $\alpha_1 = 0.0104$ and $\Delta\beta_1$= 0.125; propagation stage lasts 5 years, $\alpha_2 = 0.025$ and $\Delta\beta_2$= 0.125; deterioration stage takes 5 years before the bridge deck fails, $\alpha_3 = 0.05$ and $\Delta\beta_3$= 0. 25. Two maintenance strategies are available: (a) preventive maintenance (PM): replace the deck surface every 12 years and (b) essential maintenance (EM): replace the entire deck when it fails (approximately every 22 years), and the corresponding reliability improvements are presented in Fig. 4. Social attributes-related parameters are provided in Table 2. The minimum and maximum values of social attributes are calculated and presented in Table3.

The life-cycle social utility values of the bridge considering no maintenance, replacing the deck surface and replacing the entire deck are computed based on data provided in Tables 2 and 3. Equal weighting is applied herein to combine the utility values of various social attributes. The life-cycle social utility values with $\gamma = \pm 1$ are presented in Fig. 5. Results indicate that replacing the deck surface every 12 years (PM) shows higher life-cycle utility value, while no maintenance and replacing the entire deck (EM) have relatively lower utility values regardless of the risk attitude of decision makers. Compare with essential maintenances, preventive maintenances cause less disturbance to the normal

Fig. 3. Highway bridge for case study

Table 2. Variables in the social-attribute evaluation

Variables*	Mean	Cov	Distribution	Reference
f_d (m)	55	0.20	LN	Sabatino, Frangopol, and Dong, 2014
O_r	1.56	-	Deterministic	
TT_p (%)	4	-	Deterministic	
$c_{w,car}$ (CNY/h)	49.23	0.20	LN	Wang, Jin, Dong, and Frangopol, 2018
$c_{w,truck}$ (CNY/h)	64.10	0.20	LN	
$c_{r,car}$ (CNY/km)	0.42	0.20	LN	
$c_{r,truck}$ (CNY/km)	0.896	0.20	LN	
A	35000	0.20	LN	Based on local traffic
D_l (km)	25	0.20	LN	
S (km/h)	85	0.20	LN	
K_{road} (km)	33	-	Deterministic	
$d_{t,a}$ (days)	180	0.20	LN	Assumed
$d_{t,b}$ (days)	365	0.20	LN	
NF_a (dB)	70	0.20	LN	GB 3093-2008
NF_b (dB)	85	0.20	LN	
NFL (dB)	65	-	Deterministic	
Δt_a (days)	30	0.20	LN	Assumed
Δt_b (days)	60	0.20	LN	
ΔR_A (CNY/day)	1.85e5	0.20	LN	Based on local economic statistics
ΔR_I (CNY/day)	1.82e6	0.20	LN	
ΔR_T (CNY/day)	4.48e6	0.20	LN	
ΔR_R (CNY/day)	9.40e6	0.20	LN	
ΔR_O (CNY/day)	3.49e5	0.20	LN	

*Subscripts ‘a’ (or ‘b’) represents that the parameter is associated with maintenance strategy (a) (or (b)).

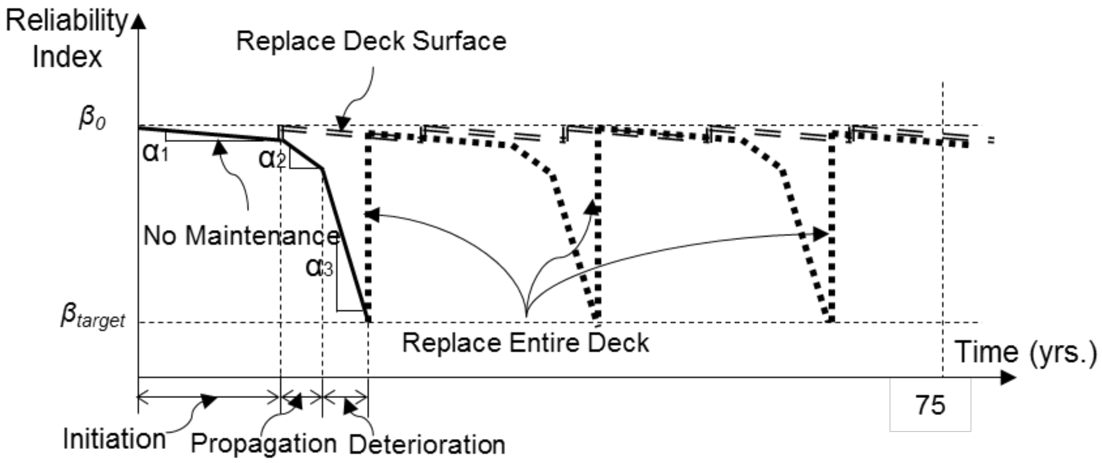

Fig. 4. Reliability evolution of bridge deck with no maintenance or with two maintenance alternatives

Table 3. Minimum and maximum values of social attributes

	Attribute	Minimum	Maximum
Social Benefits	TD	0	0.135
	ATI*	0	297
Social Burdens	FT	0.0101	0.1297
	IL (CNY/day)	0	1.47×10^6
	PL (CNY/day)	0	6.72×10^6
	NP	0	0.635
	ΔSR (CNY/day)	0	1.62×10^7

*The maximum value of ATI is calculated by multiplying the maximum availability scale 9 by the total length of the two bridges 33km.

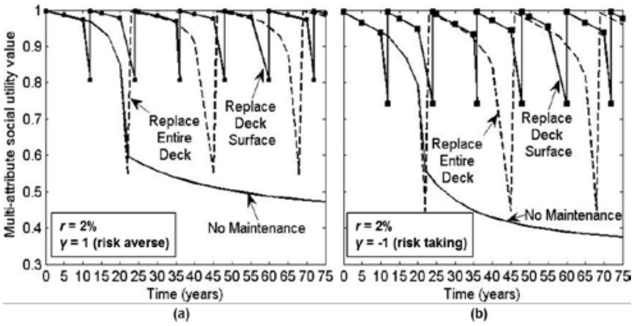

Fig. 5. Multi-attribute social utility values of different maintenance strategies with (a) $\gamma = 1$ and (b) $\gamma = -1$

function of the bridge, and hence have less social impacts. Decision makers' risk attitudes also have obvious effect on the utility values. A risk-taking attitude produces lower utility values, which indicates that the decision makers are ready to accept worse social performances.

5.0 CONCLUSIONS

The main contribution of this paper is the identification and quantification of a series of social impacts from the viewpoint of structural engineers. Social dimensions including physical impacts, psychological impacts, economic impacts, human settlements, social-economic development and social facilities are presented, and the computational approach for corresponding social indicators is provided, including fatalities, trust degree, income loss, property loss, noise pollution, social revenue loss and availability of transport infrastructure. The utility functions for social benefits and social burdens are presented, and utility theory is applied to normalize and combine different social attributes. A deteriorating reinforced concrete (RC) bridge is used as an example to analyze the multi-attribute social utility values associated with different maintenance strategies. Preventive maintenance is proved to have less disturbance to the personal and social situation, and thus has higher life-cycle social utility value. Decision makers' risk-accepting attitudes can produce lower utility values, since it means they can accept worse social performances.

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