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Heinrich's pyramid and occupational safety: A statistical validation methodology

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A B S T R A C T

Heinrich's pyramid, which postulates that the severity distribution of occupational accidents is relatively constant, is one of the main tools for management of occupational safety. However, existing evidence suggests that decreases in minor accidents have not always been followed by similar decreases in serious and fatal accidents. To test the statistical validity of the pyramid, we propose a Bayesian two-part model: the first part estimates accident rates using a Poisson-gamma distribution, and the second part estimates the proportion of minor, serious and fatal accidents using a Multinomial-Dirichlet distribution. If this proportion does not change when the accident rate is reduced, then the statistical validity of the pyramid is confirmed, but if it changes, then its validity is refuted. Our data cover more than 50,000 companies observed over 28 months in Chile. Heinrich's pyramid is confirmed to be statistically invalid for different economic activity sectors and geographic regions, but the discrepancy is so small that, for practical purposes, the pyramid is valid. We thus conclude that the occurrence of minor accidents is a useful signal for assessing and forecasting the overall safety performance of a firm.

1. Introduction

Heinrich's pyramid (Heinrich, 1932; Heinrich et al., 1980) is among the main premises on which occupational safety management is based (Khanzode et al., 2012). It suggests a strong correlation between the occurrence of near-misses, minor accidents, serious accidents (requiring hospitalization) and fatalities (immediate death or within three months) because most of these have common causes (Gnoni et al., 2013; Lozada-Larsen and Laughery, 1987). Consequently, the reduction of a certain kind of risk is seen as correlated with reductions in accident frequency at all severity levels. As an example, Kines (2002) studied the falls of construction workers, finding that while most falls are from low heights and are therefore minor, some are from medium heights with serious effects, and others are fatal. Accident rates of different severity are correlated not because accidents of medium severity can cause fatal accidents but because construction falls have common causes that generate a certain propensity of occurrence. More generally, risk factors generate a probability distribution that indicates proportions of minor, serious and fatal accidents.

The pyramid is a methodological tool widely used in academic research. Hale (2001) recommended building pyramids by "deviation" (or last event that deviates from normal), as was done by Jacinto and Soares (2008) for the mining and quarrying industry in Portugal and by Konstandinidou et al. (2011) for the petrochemical industry in Greece. In practice, the statistical relationship between minor accidents (which are frequent), serious accidents (which are rare) and fatal accidents (which are very rare) allows companies to monitor their own propensities to experience the latter type of accident. When the number of minor accidents increases, Heinrich's pyramid predicts that serious accidents and fatalities will increase as well, which should prompt the company to improve its prevention efforts (Bourassa et al., 2016). Thus, the occurrence of minor accidents is a useful signal for assessing and forecasting the overall safety performance of a firm. However, the assumptions underlying the pyramid have been questioned (Manuele, 2011). Shanon (1980) challenge the claim of Heinrich et al. (1980) that accidents of different severity have essentially common causes. As will be shown below, our validation technique focuses precisely on this point. Hale (2001) offers a different objection, arguing that the pyramid has been used indiscriminately, as if merely preventing minor accidents would automatically reduce serious accidents.

The argument we address, which questions the usefulness of the pyramid as a descriptive and, above all, predictive tool, is whether the correlation that the pyramid suggests actually exists. There is ample evidence of disasters befalling companies with very low rates of minor accidents: the Tesoro refinery in Anacortes, Washington (2010, five deaths), the Massey Energy mine in West Virginia (29 deaths), the

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British Petroleum Deepwater oil rig in the Gulf of Mexico (11 deaths) and the PG & E pipeline in San Bruno, California (four deaths), among others (Krause, 2011). More generally, while the occurrence of non-fatal accidents in the entire U.S. workforce has fallen by 51% in the last 15 years, fatal accidents decreased by only 25.5% (Martin and Black, 2015). A similar phenomenon is occurring in other developed countries and in various industries. Consequently, various parties have called for reform of risk management systems, arguing for a prevention model focused on high-damage potential precursors (Nash, 2008). The main question of our study is the following: Does a reduction in the number of accidents at the base of the pyramid correlate with a proportional decrease at its tip? If so, our study would provide evidence in favor of a broad safety management model in which preventing all types of accidents would relate (not necessarily by causation) to a decrease in the occurrence of serious or fatal accidents. If not, and the validity of Heinrich's pyramid is refuted, then the case for a prevention model focused on high-impact accidents would be strengthened.

To address our question, we use a conjugate two-stage Bayesian model (Bernardo and Smith, 1994; Lee, 2004). Although Bayesian models have been used extensively in modeling occupational safety, the two-stage specification used in this study has not, to the best of our knowledge, been used previously in the context of occupational safety. The first stage models the total number of accidents, using a Poisson counting process, with heterogeneous incidents by company based on a Gamma distribution (Marcoulaki et al., 2012). The second stage models accident severity (minor, serious and fatal), conditional on the total number, based on a Dirichlet-multinomial distribution with heterogeneous probabilities. The proposed model is based on a Bayesian approach that allows each company in the sample to have specific characteristics with regard to both accident incidence and accident severity. This division of the model into stages allows us to analyze the impact of a decrease in the incidence of accidents (first phase) on the proportion of minor, serious and fatal accidents (second stage). If the proportions do not change, then the pyramid is statistically valid; otherwise, its validity is refuted.

Using the Chilean Safety Association's ("Asociación Chilena de Seguridad" or ACHS, in Spanish) database of occupational accidents, we estimated the proposed models, the analysis of occupational accident rates and Heinrich's pyramid test. The ACHS is an association of companies and workers in Chile whose main purpose is the prevention of occupational accidents and illnesses and the promotion of a culture that ensures the safety, health and quality of life of workers. The database available for this study includes over 50,000 companies observed over 28 months. The estimates of the models based on the ACHS database exhibit satisfactory goodness of fit, which means the Bayesian specification of the model is adequate. The estimates also show that for the incidence of accidents, it is preferable to separate the estimates by economic activity sector, while for accident type probabilities, the global model that considers all companies together is appropriate.

To test Heinrich's pyramid, we correlated the estimated incidence of accidents with the estimated probabilities of minor, serious and fatal accidents at the company level. Our results show that in the electricity, gas and water sectors, the pyramid hypothesis is valid, while in the fishing, mining and quarrying and construction sectors, the hypothesis is valid for minor to serious accidents but not for fatal accidents—that is, decreasing the accident rate does not affect the proportion of minor and serious accidents but does affect the proportion of fatal accidents. In other economic sectors, the pyramid hypothesis is not statistically valid because there is a significant correlation between the total accident rate and the proportion of minor, serious and fatal accidents. However, the economic significance of this result is sufficiently weak that, in practice, this proportion is maintained for different accident rates. This would suggest that reducing the total accident rate does impact the occurrence of serious and fatal accidents. Consequently, our findings support a broad model of safety management, where keeping track of minor accidents is a valid tool for assessing the overall safety performance of a firm.

The remainder of this paper is organized as follows. In Section 2, we present a theoretical framework, with hypotheses that may explain why Heinrich's pyramid is invalid. In Section 3, we describe the main characteristics of the proposed statistical model, while in Section 4, we describe the database used. In Section 5, we present estimates of the proposed models, followed by statistical validity tests and our economic interpretation. Finally, in Section 6, we discuss the conclusions and limitations of our study.

2. Theoretical framework

Khanzode et al. (2012) conceptualize the theory underlying the pyramid in terms of a five "dominoes" logic: (i) culture and social environment, (ii) human failure, (iii) unsafe action or situations, (iv) accidents and (v) injuries to persons. According to Heinrich (1932), removal of any of these dominoes, particularly the behavioral one (ii), stops an incident from propagating itself. One of the most controversial assumptions of the pyramid is that all accidents, regardless of severity, are triggered by "common causes" (Heinrich, 1932; Kines, 2002). Hence, when these causes are mitigated, there is a proportional reduction in minor, serious and fatal accidents. For example, Lozada-Larsen and Laughery (1987) studied 7131 minor and serious accidents in a manufacturing company over five years, finding that a large proportion of individual incidents (i.e., not catastrophic incidents involving multiple deaths) are produced by identical causes. Basford (2017) compiled data from the Bureau of Labor Statistics for the years 2006 through 2014 of rates of other recordable incidents, restricted work, lost time, and fatality incidents. After classifying companies according to primary industry sector (first digit) from the North American Industry Classification System (NAICS), he observed that decreases in severity levels are very much alike, providing support for the Heinrich Pyramid.

On the other hand, several studies have raised doubt about the common causes assumption (Petersen, 1989; Salminen et al., 1992), compelling the original authors to reinterpret it: "[Different] things cause severe injuries [from those that cause] minor injuries; thus, there are different ratios for different accident types, for different jobs, for different people, etc." (Heinrich et al., 1980, pp. 64–65). Consequently, Gallivan et al. (2008) analyzed three sets of incidents that can be categorized by severity: outcomes for emergency room patients; medication errors of different severities, as reported in 11 different studies; and relative proportions of road traffic accidents reported in Great Britain between 1993 and 2003. In none of these cases was Heinrich's pyramid observed.

Although it is clear today that the causes of minor, serious and fatal accidents are not identical, the pyramid would remain valid if these causes were strongly correlated. Using Kines's (2002) example of construction worker falls, it would be necessary to verify that the causes of fatal falls (which occur predominantly in the afternoon and result from failure to use personal protection) and of serious falls (which occur in the morning due to a lack of risk awareness) are correlated because the company does not train its employees to work at heights (Brahm and Singer, 2013) or does not implement protocols for using infrastructure to fasten harnesses or fails with regard to any other prevention measures. To that end, it would be necessary to conduct a detailed forensic study (Dźwiarek, 2004; Nenonen, 2011; Martin and Black, 2015). Thanks to the sophistication and standardization of accident records, it is now possible to employ a systematic methodology in performing this task (Jacinto and Soares, 2008; Konstandinidou et al., 2011). However, in developing countries like Chile, this is not feasible on a large scale, due to the variety of forms of registration and classification and, more importantly, the diversity of risk management systems.

To investigate the statistical validity of Heinrich's pyramid, one option is to observe each company over a period of many years and verify that when the total accident rate declines (increases), the rate of