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REINVIGORATING ENGINEERED NOISE CONTROLS: A SYSTEMS APPROACH

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Abstract

Objectives: Hearing loss is a major worldwide health issue affecting an estimated 1.5 billion people. Causes of hearing loss include genetics, chemicals, medications, lifestyle habits such as smoking, and noise. Noise is probably the largest contributing factor for hearing loss. Noise arises from the workplace, ambient environment, and leisure activities. The easiest noise sources to control are workplace and environmental. Workplace noise is unique in that the employer is responsible for the noise and the worker. Also, workers may be exposed to much higher levels of noise than they would accept elsewhere. Employers follow the traditional hierarchy of controls (substitution/engineering, administrative, personal protective equipment [PPE]). Substituting or engineering a lower noise level actually reduces the hazard present to the worker but demand more capital investment. Administrative and PPE controls can be effective, but enforcement and motivation are essential to reducing risk and there is still some hearing loss for a portion of the workers. The challenge is to estimate the costs more clearly for managers. A systems engineering approach can help visualize factors affecting hearing health. **Material and Methods:** In this study, a systems engineering causal loop diagram (CLD) was developed to aid in understanding factors and their interrelationships. The CLD was then modeled in VenSim. The model was informed from the authors' expertise in hearing health and exposure science. Also, a case study was used to test the model. The model can be used to inform decision-makers of holistic costs for noise control options, with potentially better hearing health outcomes for workers. **Results:** The CLD and cost model demonstrated a 4.3 year payback period for the engineered noise control in the case study. **Conclusions:** Systems thinking using a CLD and cost model for occupational hearing health controls can aid organizational managers in applying resources to control risk. Int J Occup Med Environ Health. 2023;36(5):672–84

Key words:
hearing loss, noise, personal protective equipment, occupational health, noise-induced, systems analysis

INTRODUCTION

The purpose of this paper is to explore the application of systems thinking to help occupational health (OH) professionals communicate hearing health risks to organizational managers. Applying systems thinking to complex processes may help justify more expensive short-term investment in control measures when long-term consequences and costs are better understood by managers.

Burden of hearing loss

Hearing health, combining hearing ability and tinnitus, is important. At the individual level, hearing health

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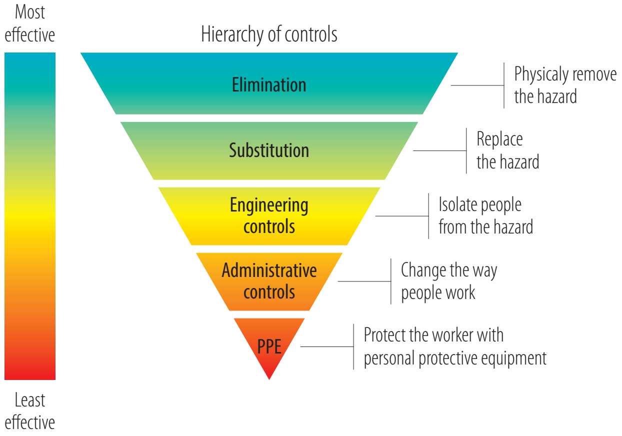


Materials developed by U.S. National Institute for Occupational Safety and Health. Reference does not constitute endorsement or recommendation by the U.S. Government, Department of Health and Human Services, or Centers for Disease Control and Prevention [9].

Figure 1. Hierarchy of occupational health risk controls

impacts stress, cardiovascular disease, and cognition [1]. It is a global issue, with the World Health Organization (WHO) estimating 1.5 billion people suffering hearing loss [2]. Hearing loss can arise from genetics, disease, pharmaceuticals, chemicals, and noise. The WHO has launched an effort to reduce hearing loss, with a primary goal the improvement of early auditory screening and clinical treatment of diseases affecting hearing [3]. Screening and clinical treatment is excellent in slowing the progress of hearing health damage and ameliorating related effects. Prevention of hearing health damage should also be a primary focus of effort so that hearing ability can be preserved. The WHO also reports an initiative to reduce noise exposure [4]. Noise is a large cause of preventable hearing loss and tinnitus. It can arise from the workplace, or from an individual's environment, personal habits or pastimes. Nelson et al. [5] estimated that 16% of the global burden of hearing loss arises from occupational noise. Zhou et al. [6] studied the distribution of occupational noise-induced hearing loss and reported that there is a disparity of disease burden, with a disproportionate burden shifting to the industrially-developing world. Workplace noise is the responsibility of the employer, and thus may be the most amenable noise source for implementing occupational and environmental health risk control strategies. The International Organization for Standardization (ISO) Quality Management Systems standard 9001:2015 defines risk as a function of probability of an outcome and the severity of that outcome [7]. Occupational health risk, the risk to workers' health arising from their occupational exposures to hazards, is one of the many risks that organizations must consider as part of their overall quality management system. One quality management researcher surveyed 28 management experts from international certification bodies and manufacturing and found that only 4 included OH risk as part of their top considerations [8]. Chiarini [8] therefore considered that the identification of OH risk resulted from personal opinion and excluded it from further study.

Hierarchy of OH risk controls

A typical OH risk management construct is to meet regulatory requirements for the nation in which the organization is located. This "compliance" construct seeks the minimum required investment of time and resources in both capital and operations and maintenance (O&M) funds to avoid adverse government enforcement action. The organization must decide on the optimum number, type, and quality of OH professionals. It must also determine the appropriate suite of OH risk controls. In the traditional paradigm of OH risk controls, there is a hierarchy based on effectiveness (Figure 1). Elimination or substitution of a process or chemical removes the hazard from the worker. An engineered control such as local exhaust ventilation to remove an airborne contaminant or a sound barrier to reduce a noise level, reduces the hazard present to the worker. Administrative controls such as training or limiting exposure duration, do not remove or reduce the hazard, but seek to reduce the dose received by the workers. The lowest OH control is personal protective equipment (PPE). Personal protective equipment is worn by the worker to reduce the dose received from the hazard which is still present to the worker. It can be an effective control, but each exposed worker must maintain and wear the PPE correctly at all times when exposed. Therefore PPE should be considered only after higher level, more effective control options have been considered and enacted. Or PPE may be selected when higher control options have been considered too costly or only partially effective. Some nations regulate the selection of a suite of OH controls, but in many countries, the exact suite of controls to reduce OH hazards to acceptable levels is left to the organization.

Businesses are complex systems managing risk

Almost all organizations are complex systems. Commercial organizations are certainly complex. A manufacturing organization includes raw materials, processes, machinery, maintenance, workers, market share, competition, finances, and many more variables. Employers have the responsibility to control occupational and environmental hazard risk, but also to sustain the commercial organization. They must decide where to apply resources (time, money, attention) to maximize gains and minimize losses.

Outside of the entertainment industry, noise is not the goal of commercial organizations, but rather a byproduct of industrial processes. However, the control of noise is also not the commercial goal. Commercial organizations are driven by profit. Profit is realized when gains exceed losses. One component of losses is costs, where financial resources are spent. Costs can be broken into capital investment and O&M costs. Commercial organizations seek profit by applying limited financial resources, personnel time, and attention to managing risk.

There are 2 types of risk, opportunity and pure. Opportunity risk can be positive or negative. A capital investment may result in more market share, or an improved production efficiency (gain). A capital investment may also fail to realize the increased market share and become a negative (loss).

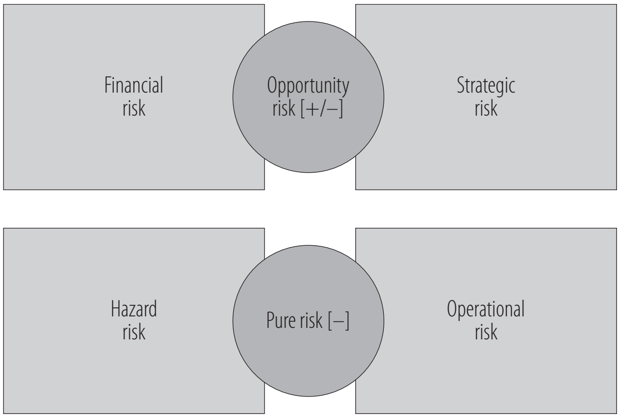


Figure 2. The 4-quadrant model of organizational risk (based on [10])

Four quadrant model of risk

In the 4-quadrant description of organizational risk [10], OH risk is considered a hazard risk. It is a "pure risk" on the bottom half of the pie chart in Figure 2. This means that it will only cost the organization (loss). It cannot result in an increase in revenue (gain). This encourages organizational behavior seeking a "least loss" strategy when considering OH risk. Organizations make decisions to apply resources based on long and short term expected results, maximizing gains and minimizing losses. A successful organization can apply a strategy for both long and short term net gain. Too much focus on short term prevents the organization from investing in preparations to succeed in the long term. Ignoring short term issues leads to lack of nimble response to shifting pressures, which can also result in loss. It is often easier to perceive the short term risk tradeoffs than the long term. There is also more uncertainty in long term risk tradeoffs than short term. All of these characteristics aid in understanding the complex system of variables which influence the selection of OH risk control measures.

Hierarchy of OH risk controls often not followed by commercial organizations

A source of this long term risk tradeoff uncertainty is the linkage between inputs and expected outputs. When considering OH risk, inputs from the hierarchy of controls give outputs of lower risk of probability and severity of health impacts. Higher level controls (substitution and engineering) tend to demand more capital investment. Lower level controls tend to cost incrementally much less in capital; the cost per worker is less. An unintended consequence of the OH risk management construct is that the larger capital investments in higher level, more effective risk controls are difficult to justify. The links between capital expenditure and risk control are not clear for several reasons.

The manifestation of OH health problems can be either stochastic or non-stochastic. Stochastic health outcomes tend to follow a dose-response model with no threshold. Increasing dose increases the disease burden. Non-stochastic health outcomes also follow a dose-response relationship, but with a threshold below which no permanent health problems arise. Hearing health tends to be a non-stochastic health outcome. There is an acceptable level of noise to which the ear can be exposed without any permanent damage. Increasing the noise dose increases the probability of hearing loss in both proportion of the exposed population and degree of damage. A given hazardous noise exposure may not cause hearing loss in all exposed individuals. Also, most hearing loss is chronic in nature, increasing with longer exposure over the years of employment. An organization's manager may not be able to clearly perceive how noise exposure will eventually lead to hearing loss in some number of employees in 10–30 years. They may also consider whether their diagnosed hearing loss rates per year are any worse than other similar organizations. The workers with hearing loss may still be able to work, and the other symptoms of stress and anxiety from hearing loss or tinnitus may not be apparent.

In contrast, the organization's manager can clearly see the cost of the OH department's budget, and the cost for the noise risk controls. Personal protective equipment such as ear plugs or muffs, generally referred to as hearing protection devices (HPD) is much less expensive than an engineered noise control. That allows more money for investing in opportunity risks to grow revenue. Clearly higher level OH risk controls reduce the noise present to the workers and will reduce hearing loss and tinnitus more than lower level controls such as HPD. How can the OH department more clearly show the relationships of variables which contribute to hearing loss, as well as the effects of hearing loss on the organization to justify investment in higher level risk controls?

Systems thinking and causal loop diagrams for commercial organizations

Commercial organizations are complex. Systems thinking and causal loop diagrams (CLDs) have been utilized to aid understanding of complex business relationships. Within a text book on computer simulations for commercial supply chains, Campuzano and Mula [11] applied CLDs to aid understanding. Further, the workers' interaction in the commercial process is complex. Systems thinking has been used to illustrate the complex interaction of humans with each other and their environment [12–15]. A very useful tool for applying systems thinking to a commercial organization is the CLD.

A brief introduction to CLDs

Causal loop diagrams have been used for many years to help understand complex processes, arrive at common understanding of those processes, and understand human factors relationships [16]. They have also been applied to environmental compliance [12], and occupational safety [14,15,17,18].

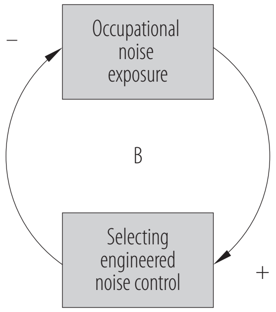
Aikenhead et al. [12] developed simplified process diagrams and CLDs for a small dairy plant in Canada. They used the diagrams to engage workers and management to look for opportunities to reduce pollution. Together they estimated a savings in raw milk wastage, water use, and biochemical oxygen demand pollution fines of USD 175 000 annually.

Su-Wuen et al. [13] applied CLDs to air transportation safety in New Zealand. They recognized the complex interplay between machines, organizations, processes, people, and market forces. Their CLD had 3 unique subsystems of business operations, human resources, and safety. They assert that their CLD aids in understanding of airline safety by including the many variables influencing the safety outcomes.

Balaji [15] reported success in developing and applying a generic CLD to understand and improve personnel safety management. The generic CLD was then parameterized and applied to a case study of a steel manufacturing facility in India. The research sought an optimal application of hazard identification, hazard removal, reporting, and incidence correction rates to effect the minimal incident rate. It did not include human factors from management and worker interactions and behaviors, but was helpful in understanding the relationships of the variables which could be measured.

Wu et al. [14] applied CLDs to explore the relationships of lean construction on occupational safety using data from 448 construction projects in China. They modeled the various lean construction subsystems and found that the increased focus managing the complex construction processes correlated to better occupational safety performance as well. This does illuminate the management environment influence over worker adoption of safety measures.

Guo et al. have been researching the application of systems thinking to construction safety for many years. In 2018, they incorporated behavior-based safety into a systems thinking CLD for construction safety. They recognized the human factor in safety and developed a model to fit existing data on worker safety performance, with dynamics of goal commitment, punishment, and monetary incentive standing out as critical variables [18]. Worker behavior is an essential component for any safety measure such as PPE where the hazard is still present to the worker and the safety measure must be utilized correctly every time there is a hazard. Maryani et al. [17] developed a CLD to describe the system dynamics of variables affecting construction safety. They did include worker characteristics (safety awareness, education, years of work experience, etc.), type of construction work, safety management, and safety protection systems, but did not include finer variables of the effectiveness of the PPE, worker conformance to protocols or other safety and health controls.

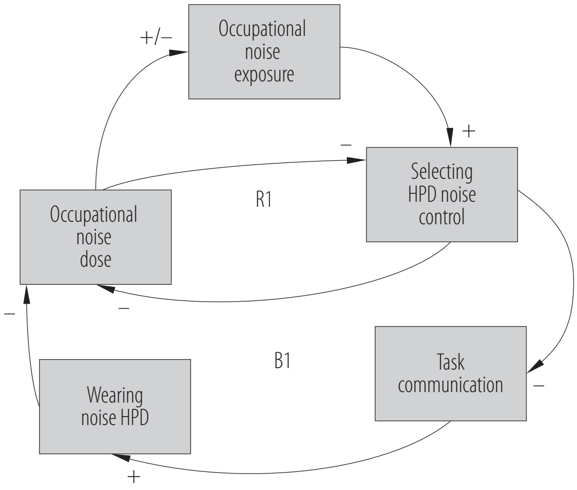


B – balancing feedback loop.
"+" – a positive relationship; "–" – a negative relationship.

Figure 3. Simple causal loop diagram for occupational noise exposure and control

The authors would propose a systems thinking CLD for hearing health as a technique to help organizational managers understand the complex system of variables which impact hearing health, how hearing health affects their success, and to search for opportunities to improve the system towards a goal. The proposed CLD does include a map of some of the variables from the perspective of the safety and health professionals and the workers to assist organizational managers' conceptualization of key processes.

Figure 3 illustrates a simple example CLD. The boxes are "nodes" or variables. The arrows indicate the direction of influence in the relationship. There is also a negative (–) or positive (+) sign by each arrow indicating the nature of the relationship. A negative relationship has one variable decrease as the other increases whereas a positive rela-



B – balancing feedback loop; R – reinforcing feedback loop.
"+" – a positive relationship; "–" – a negative relationship.

Figure 4. Causal loop diagram for occupational noise exposure, dose, task communication, and hearing protection devices (HPD) control

tionship has one variable increase as the other increases. The exact degree of the relationship does not have to be reduced to a Cartesian graph or mathematical formula. Sometimes they can be, but often the relationship is simply informed qualitatively by literature review or interviews with people having expertise in the system.

The loops of a CLD can be balancing or reinforcing. Balancing loops are indicated by "B" on the diagram and tend to keep system behavior within some limits. Reinforcing loops "R" tend to allow the system to increase or decrease out of control. A general rule is that an odd number of negative (–) arrows indicates a balancing feedback loop. An even number of negative (–) arrows indicates a reinforcing feedback loop.

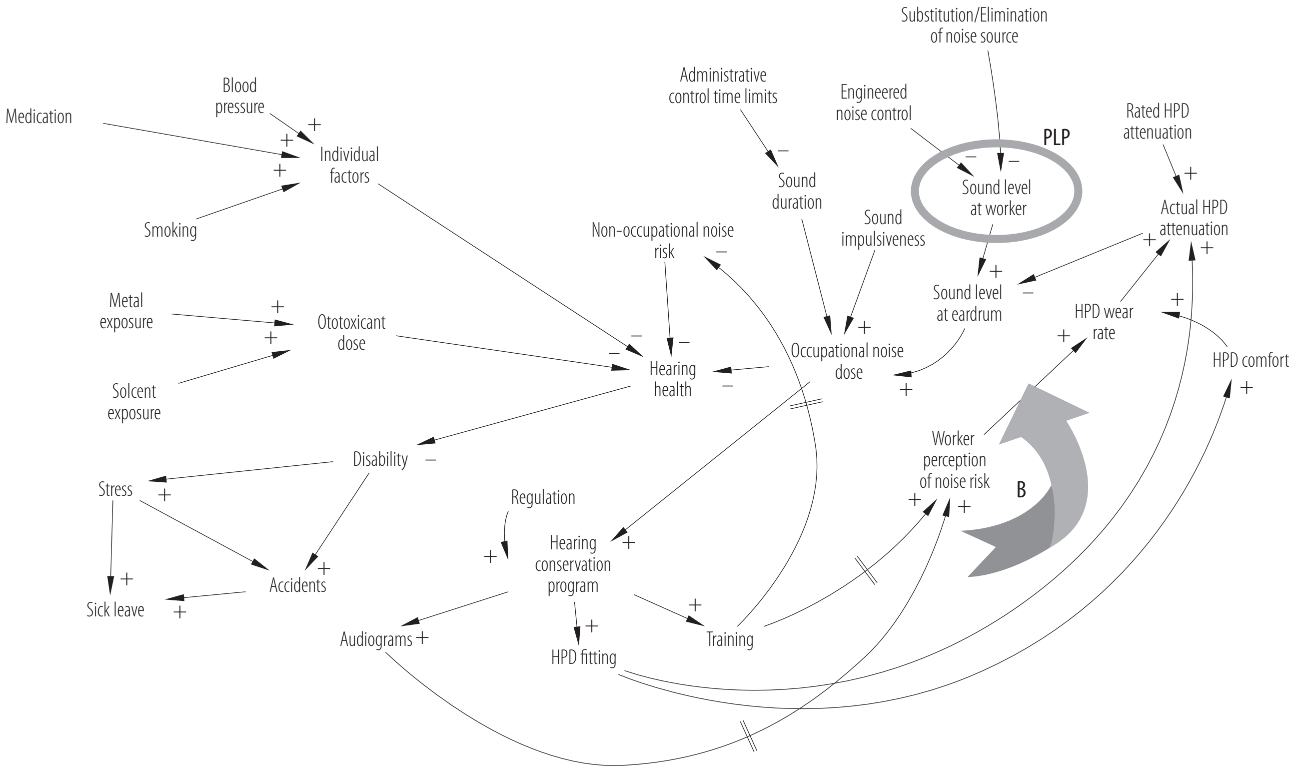
In the example "balancing" loop in Figure 3, increased occupational noise exposure would encourage selection of effective engineered noise controls, which would decrease the occupational noise exposure. This relationship would tend to balance the noise exposure to workers, hopefully to an acceptable level of residual risk.

As previously stated, various factors tend to encourage organizations to select a lower level OH risk control such as HPD. While ostensibly controlling the dose to the worker, there are other factors involved when estimating the degree of protection afforded. The CLD in Figure 4, illustrates some of the variables when HPD controls are selected instead of engineering noise controls to decrease the occupational noise exposure as in Figure 3. In Figure 4, increased occupational noise tends to increase the selection of OH risk controls, such as HPD. However, selecting HPD does not change the occupational noise exposure. The noise is still all around the worker and his colleagues. Adding some complexity to the CLD helps make it more useful in describing real-world relationships.

Figure 4 shows the selected HPD does reduce the noise dose to the worker. Because the dose is lower, then hearing loss should be less. As noise dose decreases, the frequency of selecting HPD increases. This would encourage the selection of HPD as a noise control. However, the second feedback loop in Figure 4 illustrates how task limits (like the need to communicate) lead to imperfect compliance with HPD controls. Workers will remove their HPD to communicate if the task demands communication. As more HPD is selected, the workers can communicate less (–). As workers lose communication ability, they wear HPD less (+). As workers wear HPD less, their noise dose increases (–). As noise dose increases, HPD is selected less often (–). The new feedback loop has an odd number of (–) arrows, so it is a balancing loop.

This CLD shows how the tendency to select HPD as a control should be balanced as HPD tends to fail in some cases and results in higher noise dose on average.

The utility of CLDs is the presentation of relationships within complex systems. The CLD also allows the complex system to be visualized and understood by a larger group. They can share a "common operating picture" of the system. When the manager directs an action affecting 1 or several of the variables, the team can expect the impacts to other variables in the system. When a manager is considering several options for investing



B – balancing loop; HPD – hearing protection device; PLP – potential leverage point.

Figure 5. Causal loop diagram describing hearing health

resources, the expected outcomes from the various courses of action can be compared. In most complex systems, there are variables which, when acted upon, may return a larger systematic response than other variables. These potential leverage points (PLPs) can be useful variables for a manager to be aware of so that a smaller application of resources may have a larger effect on the system – a more efficient application of limited resources. In complex systems, the PLPs are not always readily apparent and a method to identify PLPs would be helpful.

CLDs to help identify PLPs

Roxas et al. [19] reviewed the literature to distill a method to identify PLPs from a CLD. These are the criteria:

- is a common cause to multiple effects that can accelerate or decelerate the operation of a system,
- can be influenced by an intervener,
- is the root cause characterized by being independent (i.e., cannot cite further causes).

The criteria do not guarantee that the selected CLD variable is a PLP, but they do suggest it. Knowing the PLPs for a complex system aids a manager in efficiently applying resources to the system to achieve desired goals, such as maximizing net profits. A CLD describing OH risks from the organization's operations can be helpful for a manager to understand the consequences of their OH risk control decisions.

MATERIAL AND METHODS

A proposed CLD for hearing health

Consider a larger CLD describing hearing health and the causal factors which affect it, and which it affects, in Figure 5. The CLD was developed using VenSim personal learning edition (PLE) software (Ventana Systems, Inc., Harvard, MA, USA) for educational use.

Description of CLD

At the center of this CLD is hearing health. The CLD shows 4 main variables which affect hearing health; occupational noise dose, non-occupational noise risk, ototoxicant dose, and individual factors. Hearing health is itself a causal factor to disability. All of these causal relationships are negative (e.g., as occupational noise risk increases, hearing health decreases).

On this CLD, there is a feedback loop from occupational noise dose to hearing conservation program (HCP – an administrative OH control), training, worker perception of noise risk, HPD wear rate, HPD attenuation, sound level, and back to occupational noise dose. This loop has a single negative (–) sign, so it would be a balancing loop. There are similar loops for HCP to HPD fitting, and HCP to audiograms. However, while perfect HPD use can attenuate noise, the sound level, duration, and impulsiveness still present an occupational noise risk. Also, the occupational noise risk affects both hearing health and the HCP.

The sound at the worker is a PLP where resources invested to change and reduce that sound would make a large change in the system. This can be used to show the manager that it might be worth investing resources to engineer a lower sound level, reduce duration and impulsiveness, and thereby reduce the occupational noise dose. This should also reduce disability, stress, accidents, and sick leave in the workforce. But how many resources should be applied to influence this PLP? How much cost savings can be realized by an investment in engineering controls or substitution? A simple model estimating the costs of applying HPD controls for a noise hazard is presented.

Simple cost model for HPD noise controls

There are several components of a cost model arising from the selection of HPD to reduce noise hazard risk. Many of them depend on the average noise level to which workers are exposed. When workers are exposed at or above an average 8-hour daily equivalent continuous level ($L_{eq,8h}$) of 85 dB, A-weighted (dBA), then there is a risk to their hearing health. An HCP is then required, consisting of annual audiogram examinations, selection and fitting of HPD, training on the hazards of noise exposure and methods to protect oneself, and administration of the program. All of these components require resources in funds and time. At many small or medium-sized organizations lacking medical teams, the audiograms are contracted by a third party.

Workers do not wear their HPD uniformly across exposure levels. Very few workers wear hearing HPD when exposed below the average occupational limit. There is a threshold where workers are considered "hazardous noise exposed" at $L_{eq,8h}$ = 85 dBA. At this level, workers are more likely to wear HPD, but not at all times [20]. Many more workers wear HPD at 86 dBA than at 84 dBA. However, many still do not consistently wear their HPD. Neitzel and Seixas [20], found that construction workers exposed at 85 dBA L_{eq} and 90 dBA L_{eq} had very similar HPD use rates, approx. 17% of the time they were exposed at those levels. This results in a lower PPE noise attenuation than expected and higher average sound level at the eardrum of exposed workers.

Also, as the at-eardrum sound exposure level increases, the fraction of exposed workers expected to lose some hearing increases. The International Organization for Standardization (ISO) publishes a guide for estimating the expected level of hearing loss among a portion of a population at a given average noise exposure level, ISO standard 1999:2013 [21]. The standard makes it possible to estimate hearing loss for a group of workers exposed at a certain average sound level. This information can be used to estimate the costs of hearing loss. There are a variety of definitions of hearing loss. The United States National Institute for Occupational Safety and Health (NIOSH) recommends using the permanent threshold shift (PTS) definition of a change in hearing level equal to or exceeding 15 dB in any of the frequencies (500 Hz, 1000 Hz, 2000 Hz, 3000 Hz, 4000 Hz, or 6000 Hz). Hearing loss is also associated with the aging process. The United States Occupational Safety and Health Administration allows organizations to account for the expected hearing loss from aging so that they are not liable for hearing loss from uncontrollable circumstances [22]. In this example, the proportion of the population with a NIOSH-defined PTS not corrected for age was used. This means that some of the hearing loss could be from the aging process, which should be very low at an assumed age of 30 years.

A group of researchers examined U.S. OH data from 1999 to determine the "top 10" diseases costing American organizations. One of the diseases included hearing loss and a cost model including medical costs, short-term disability, and absenteeism, was estimated at USD 49.72 per incident in 1999 currency [23].

When combining estimated costs for HPD hearing health controls, there is a threshold where HCP costs apply, and there is an incremental cost per worker. Equation 1 below displays the simple annual HPD control costs (ControlCost$_{\text{HPD}}$) model per worker:

$$\begin{aligned}&\text{ControlCost}_{\text{HPD}}=(\%\text{PTS}_{L'}\times\text{Cost}_{\text{PTS}})+\\&+[(\text{Time}_{\text{Ad min}}+\text{Time}_{\text{Audiogram}})\times\text{Wage}_{\text{Hourly}}]+(\text{Cost}_{\text{Audiogram}})+\\&+(\text{HPD}_{\text{Daily}}\times\%\text{Used}_{\text{HPD}}\times\text{Cost}_{\text{HPD}}\times\text{Workdays}_{\text{Annual}})\end{aligned}\qquad(1)$$

where:

$\%\text{PTS}_{L'}$ – percent of population exposed at noise level L' for 10 years expected to experience a PTS (not corrected for age) of ≥15 dB (calculated according to [21]), then annualized for rate per year. The NIOSH definition of a hearing threshold shift is 15 dB at any frequency (0.5 kHz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, or 6 kHz),

Cost_{PTS} – estimated cost of a single worker experiencing a hearing threshold shift,

$\text{Time}_{\text{Admin}}$ – time [h] for a worker to administer a HCP,

$\text{Time}_{\text{Audiogram}}$ – time [h] for a worker to receive an annual audiogram,

$\text{Wage}_{\text{Hourly}}$ – assumed hourly wage of workers with benefits included,

$\text{Cost}_{\text{Audiogram}}$ – estimated cost per worker of contracted audiogram services,

$\text{HPD}_{\text{Daily}}$ – number of sets of disposable hearing HPDused by a worker,

$\%\text{Used}_{\text{HPD}}$ – percent of workers actually using HPD,

Cost_{HPD} – estimated cost of a single pair of disposable HPD,

$\text{Workdays}_{\text{Annual}}$ – assumed annual workdays.

Further, the estimated hearing threshold shift depends on noise level (L'). This average noise exposure level accounts for the attenuation afforded by HPD as well as the fact that workers do not always wear their noise HPD. The average noise level exposure calculation is given in equation 2 below:

$$L'=10\log\left[\frac{\%\text{Used}_{\text{HPD}}\times 8\,\text{h}\times 10^{\frac{L-NR_{\text{HPD}}}{10}}+(1-\%\text{Used}_{\text{HPD}})\times 8\,\text{h}\times 10^{\frac{L'}{10}}}{8\,\text{h}}\right]\qquad(2)$$

where:

L – average daily A-weighted equivalent continuous level ($L_{\text{eq,8h}}$) of exposed worker population,

NR_{HPD} – assumed noise reduction provided by HPD.

Definitions and sources used for the variables in equations 1 and 2 are given in Table 1. Several variables were assumed based on the authors' experience or consideration of a range of freely available market information on the internet. The listed assumptions can easily be adjusted to a particular national or regional market.

Also, Goetzel et al. [23] included estimates of absenteeism and the cost per hour. This was used to also estimate the cost of the HCP, assuming workers take an average of 2 h/year of paid time to get their audiogram. An aver-

Table 1. Assumed values for simple cost model with references applied to case study [24]

Variable	Assumed value	Reference
$\%PTS_{L'}$	calculated at 0.5, 1, 2, 3, 4, or 6 kHz for a 15 dB threshold shift	21
$Cost_{PTS}$	USD 86.30 (Goetzel's estimate of USD 49.72 adjusted for inflation)	23
$Time_{Admin}$	12 h	assumed
$Time_{Audiogram}$	2 h	assumed
$Wage_{Hourly}$	USD 52.06 (Goetzel's estimate of USD 30.00 adjusted for inflation)	23
$Cost_{Audiogram}$	USD 30.00 per worker	assumed
HPD_{Daily}	2 sets of HPD per day	assumed
$\%Used_{HPD}$	17%	20
$Cost_{HPD}$	USD 0.30/pair of disposable ear plugs	assumed
$Workdays_{Annual}$	250d	assumed standard 5 days/week, 50 weeks/year
L	varied input; range 80–100 dBA	assumed
NR_{HPD}	19 dB	20

$Cost_{Audiogram}$ – estimated cost per worker of contracted audiogram services; $Cost_{HPD}$ – estimated cost of a single pair of disposable hearing protection devices (HPD); $Cost_{PTS}$ – estimated cost of a single worker experiencing a hearing threshold shift; HPD_{Daily} – number of sets of disposable hearing HPD used by a worker; L – average daily A-weighted equivalent continuous level ($L_{eq,8h}$) of exposed worker population; NR_{HPD} – assumed noise reduction provided by HPD; $\%PTS_{L'}$ – percent of population exposed at noise level L′ for 10 years expected to experience a PTS (not corrected for age) of 15 dB or more (calculated according to [21]), then annualized for rate per year (the NIOSH definition of a hearing threshold shift is 15 dB at any frequency [0.5 kHz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, or 6 kHz]); $Time_{Admin}$ – time [h] for a worker to administer a HCP; $Time_{Audiogram}$ – time [h] for a worker to receive an annual audiogram; $\%Used_{HPD}$ – percent of workers actually using HPD; $Wage_{Hourly}$ – assumed hourly wage of workers with benefits included; $Workdays_{Annual}$ – assumed annual workdays.

age cost per worker for contracted audiology services was assumed, and an assumed 12 h/year of administrative burden to oversee the HCP. Scaled to an assumed working population of 100 workers, the cost of selecting HPD for a noise hazard had a steep threshold. There is some cost for HPD for loud tasks even when the average daily noise exposure ($L_{eq,8h}$) is <85 dBA and there is no required HCP. Once the average meets or exceeds 85 dBA ($L_{eq,8h}$ ≥85 dBA), then the costs for the HCP, HPD, and the possible annual rate of hearing loss costs were included. The rate of expected hearing loss increases with average noise level, but there is always a minimum cost from the HCP. This tool provides a method for managers to compare costs of selecting HPD as their noise control.

The greatest annual savings from engineering controls occurs when the engineering controls can reduce the noise <85 dBA $L_{eq,8h}$. This frees the employer and employees from the requirements for a HCP and also prevents noise-induced hearing loss. If the engineered controls can reduce the noise, but not to an average level <85 dBA, then the cost of HCP remains, but the percent of the population expected to experience a PTS is reduced. Engineering control goals should be to remove as many workers as possible from the HCP, and to reduce the noise level for all workers. In this way, savings are maximized.

RESULTS

The following is a case study from an industrial organization which the first author worked on [24].

The top manager who decided where to spend time and money, was shown the impact of the company hearing loss costs, as well as time for training, audiograms, and money for HPD. The loud task was performed by 2 workers with average daily exposures measured at 100 dBA. The incremental cost to have the 2 workers added to the existing pool of workers on the HCP was very low. Also, the task was so loud that even with HPD it could only be performed for 4 h/workshift to keep the noise dose <100%, slowing productivity. Lastly, the task was performed on the open shop floor, so that 143 other workers not involved in the task were also hazardous noise-exposed and considered for enrollment in the HCP.

The team of safety department, workers, labor union, and process engineers asked for money and time to study the problem and develop engineered controls to reduce the noise hazard. A cost model informed the complex organizational system so that the manager authorized the team's efforts and applied funds for the engineered controls.

The engineered controls were developed iteratively with a goal of protecting the other 143 workers so that they could be removed from the HCP and not expect to lose their hearing. The team designed, built, and tested a large room for the task. The room provided significant transmission loss to the direct path noise from the task to the other 143 workers. The interior of the room was treated with sound absorption materials which reduced the reflected path noise affecting the 2 workers inside the room. The total cost was USD 99 000. The project reduced the noise level to the other 143 workers by an average of 28 dBA so that none of them were hazardous noise-exposed anymore. The noise level for the 2 workers performing the task was reduced by 3 dBA. This allowed the task duration to be extended to 8 h/shift, thus doubling productivity for this task. The primary savings considered were from removing 143 workers from the HCP. Applying the calculations from the model above (not accounting for productivity), the payback period would be 4.3 years. The expected 10-year PTS burden among the 145 total workers shifted from an expected 23.6 cases of NIOSH-defined hearing loss to an expectation of 1.6 cases.

Table 2. Assumed noise exposure distribution of 145 noise-exposed workers before and after engineered controls implemented

Average daily noise[a]	Participants at given exposure level [n]	
	before engineered controls	after engineered controls
80 dBA		68
83 dBA		75
87 dBA	68	
90 dBA	55	
95 dBA	20	2
100 dBA	2	

[a] $L_{eq,8h}$ – average 8-hour daily equivalent continuous noise level.

The simple cost model was applied with the 145 workers' assumed noise exposures distributed given in Table 2.

DISCUSSION

The model estimated an annual HPD cost reduction of USD 23 246. The estimated years to pay back the initial engineering control investment of USD 99 000 was 4.3 years. This method can assist in competing for resources to reduce hazard risk. In the case study, the opportunity risk gained from the resulting doubled productivity also made the investment in engineered controls attractive. That savings was not included in this model.

CONCLUSIONS

A CLD can help managers visualize the relationships and perceive how hazard risk directly influences opportunity risk. An organizational manager can use the CLD to identify PLPs for the system. In the example case study, the manager invested time and money and received less hazard risk and more productivity. This simple cost model can aid in describing the costs associated with selecting a lower level of occupational noise hazard control, thereby justifying a capital expenditure in the short-term for long-term future sustained cost avoidance.

Author contributions

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Research methodology: Jeremy Slagley, Adam Dudarewicz, Małgorzata Pawlaczyk-Łuszczyńska

Collecting material: Jeremy Slagley

Statistical analysis: Jeremy Slagley

Interpretation of results: Jeremy Slagley, Adam Dudarewicz, Małgorzata Pawlaczyk-Łuszczyńska, Francis Slagley

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