A Probabilistic Approach for Economic Evaluation of Occupational Health and Safety Interventions: A Case Study of Silica Exposure Reduction Interventions in the Construction Sector

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Abstract

Background: Construction workers are at a high risk of exposure to various types of hazardous substances such as crystalline silica. Though multiple studies indicate the evidence regarding the effectiveness of different silica exposure reduction interventions in the construction sector, the decisions for selecting a specific silica exposure reduction intervention are best informed by an economic evaluation. Economic evaluation of interventions is subjected to uncertainties in practice, mostly due to the lack of precise data on important variables. In this study, we aim to identify the most cost-beneficial silica exposure reduction intervention for the construction sector under uncertain situation. Methods: We apply a probabilistic modeling approach that covers a large number of variables relevant to the cost of lung cancer, as well as the costs of silica exposure reduction interventions. To estimate the societal lifetime cost of lung cancer, we use an incidence cost approach. To estimate the net benefit of each intervention, we compare the expected cost of lung cancer cases averted, with expected cost of implementation of the intervention in one calendar year. Sensitivity analysis is used to quantify how different variables effects interventions net benefit. Results: A positive net benefit is expected for all considered interventions. The highest number of lung cancer cases are averted by combined use of wet method, local exhaust ventilation and personal protective equipment, about 107 cases, with expected net benefit of $45.9 million. Results also suggest that the level of exposure is an important determinant for the selection of the most cost-beneficial intervention. Conclusions: This study provides important insights for decision makers about silica exposure reduction interventions in the construction sector. It also provides an overview of the potential advantages of using probabilistic modeling approach to undertake economic evaluations, particularly when researchers are confronted with a large number of uncertain variables.

Background

Construction workers are at a high risk of exposure to various types of hazardous substances such as crystalline silica.[1,2] Crystalline silica is an abundant material that is commonly released in respirable form during different construction activities such as concrete work, abrasive blasting, demolition, excavation, earth moving, tunnel construction, and highway building.[3] Reports indicate that the level of silica exposure for numerous construction workers in Ontario, Canada exceed occupational exposure limit (i.e. 0.05 mg/m^3).[1] This is likely the case in other jurisdiction across Canada and internationally. Meanwhile, occupational silica-related diseases such as lung cancer annually impose considerable direct costs to the healthcare system and indirect cost to industry in the form of lost output and reduced productivity, as well as high intangible costs in the form of health-related quality of life losses to afflicted workers and their families.[4]

There are several silica exposure reduction interventions applicable to construction projects.[5–10] These interventions work in different ways, e.g., preventing silica dust from getting into the atmosphere; removing dust in the atmosphere; and preventing workers from inhaling the dust if present in the atmosphere. Wet method (WM) refers to the use of a using water with devices to reduce the release of

silica dust. Local exhaust ventilation (LEV) refers to the use of local vacuum systems at the point of operation to reduce the release of free silica dust into the work environment. The personal protective equipment (PPE) refers to use of the National Institute for Occupational Safety and Health approved personal protective equipment, namely respirator masks training. Enclosed work areas and work hygiene practices are some other common types of intervention options.

Though several studies provide evidence on the effectiveness of different silica exposure reduction interventions in the construction sector, the decision for choosing a specific intervention is best informed by an economic evaluation. Despite the importance of the issue, there are only a few economic evaluations of silica exposure reduction interventions. One of these studies by Lahiri et al.[7] evaluates the costs and effects of different interventions for the prevention of occupationally induced silicosis. They estimate the cost-effectiveness in terms of the dollars spent to obtain an additional healthy year. Another economic evaluation study by the Occupational Safety and Health Administration (OSHA) in the United States[5] addresses issues related to costs, technological feasibility, and the economic impacts of the proposed respirable crystalline silica rule which attempts to reduce the permissible exposure limits from its current level of 0.1 mg/m^3 to 0.05 mg/m^3. To do so, they forecast the number of silica-related diseases averted as a result of the proposed rule and compare the value of averted cases with the cost of compliance to the rule in all affected industrial sectors.

Uncertainty about the magnitude of input variables of an intervention, which has often been cited as a limitation in economic evaluation studies, can affect the precision of results.[11–12] Input data for these studies can be provided as probabilistic or deterministic values. Deterministic values should only be applied when specific values are available from a reliable source, while it is best to use probabilistic values when the reliability of information is questionable.[13] In the case at hand, we have large number of uncertain variables that impact the intervention economic evaluation results. For instance the number of silica-exposed workers and the level of exposure to silica are uncertain variables. The level of exposure is influenced by several variables such as the task, workstation characteristics (e.g. being indoor or outdoor), materials being used, phase of the construction project and other unknown variables. In many circumstances, it is not possible to collect more data on the level of exposure because of the quick pace of change on a construction project site, tasks characteristic, and/or safety requirements.[11] The risk of getting a work-related silica-related occupational disease for workers of different age and sex also has a high degree of uncertainty, since latent health conditions such as lung cancer are influenced by multiple factors not easily recognized as attributable to occupational silica exposures.[14] The cost of respiratory disease treatment is also an uncertain variable as it depends on, amongst other things, the stage of the disease and the age and sex of the individual.[15–16] In terms of the effectiveness of a silica exposure reduction interventions, the maximum is achieved by appropriate and systematic use of an intervention, which is not always the case in practice. For example, some studies suggest that the malfunction of PPE is influenced by several environmental factors such as worker's awareness, the nature of the hazard, climate, and occupational health and safety inspections.[17] The overall effectiveness of WM and LEV inetrevntions also depends on the workstation characteristics and the number of people working near

silica dust sources. Because work arrangements vary within occupations and across facilities of different sizes, there is no definitive data on how many workers are likely to be protected by a given intervention.[5–10]

There are several probabilistic modeling approach for solving problems under different levels of uncertainty, such as expected value, Markov chain, and Bayesian network (BN). Recently, the BN approach has gain popularity in different areas of health economics,[13] project cost and risk analysis,[18–20] cost-benefit analysis,[21] and occupational health and safety decision making.[22] BNs are preferred for several reasons, such as the ability to integrate various types of data (i.e., qualitative and quantitative), to combine available data with expert knowledge, to explicitly consider relationships between variables, to model complex problems with many variables involving a high level of uncertainty and to easily provide graphical representations.[18–23] The modeling languages of BNs have straightforward semantics, namely that of cause and effect. Furthermore, the needed probability calculation of BNs is often undertaken with the assistance of software packages such as Netica, GeNle, Analytica, Hugin, Bayes Net Toolbox, and many others (This is not a comprehensive list, and not meant to promote any specific software).

Methods

In this study, our objective is to identify the most cost-beneficial silica exposure reduction intervention for the construction sector in Ontario, Canada. To estimate the net benefit of each intervention, we apply a probabilistic modeling approach to compare the expected cost of lung cancer cases averted, with expected cost of implementation of each intervention in one calendar year. We anticipate this study provides important insights for occupational health policy makers and workplace parties in the construction sector. More broadly, this study provides a methodological framework for a more fulsome treatment of uncertainties in the economic evaluation occupational health and safety interventions via BNs.

Study Steps

Figure 1 identifies the main steps of our probabilistic modeling approach for the economic evaluation of silica exposure reduction interventions. First, we identify all variables that impact on the net benefit of the interventions such as the number of silica-exposed workers, level of exposure and intervention effectiveness. Variables not dependent on any other variables (called parent nodes in BNs vocabulary) have a single probability distribution, whereas variables dependent on one or more other variables (called child nodes) have a conditional probability table (dependency of a child variable to its parent's variables).[23] In the second step, we identify dependencies between variables using literature review and expert knowledge. Expert feedback also helps us to identify variables and interactions that were overlooked in the structure of the model. In the third step, we identify the probability distributions of variables, drawing on several scientific literatures in epidemiology,[24–25] occupational cancer economic burden studies,[4,16] and silica exposure reduction interventions.[5–10] Once the distributions of independent

variables are determined, we compute the probability distributions of conditional variables according to the knowledge of their parents. The main assumptions about the distribution of each variable is explained in the following paragraphs. To develop the structure of BN model and to compute the probability distributions, we use GeNIe modeller version 2.2.4 (BayesFusion, Pittsburgh University decision system laboratory).[26] Step four involves establishing the structural validity of the model. We validate the model by setting the variables to extreme values and turn to expert judgment to confirm whether the range of results (e.g. expected lung cancer cases, averted costs, and/or interventions costs) appears reasonable. Sensitivity analysis is also undertaken to quantify how different values of independent variables affect the net benefit of interventions. In the fifth and last step, we select a preferred silica reduction intervention by comparing the expected net benefit of alternatives. Benefits are the expected cost of lung cancer cases averted after implemention of different interevntions. We use an incidence cost approach and estimate the societal lifetime cost of lung cancer cases. Then we calculate expected net benefit as the difference between the expected benefit from expected cost of each interventions in a calendar year (i.e., 2020).Costs of the intervention are based on the assumption that there is no use of preventive measures at baseline. All monetary values are converted to 2017 Canadian dollars.

"INSERT Figure 1 HERE"

Input Data

To determine the probability distributions of variables, we combine our model assumptions with secondary data drawn from various sources such as the Occupational Cancer Research Centre (OCRC),[24] CAREX Canada,[25] Canadian Life Tables,[27] the Labour Force Survey (LFS),[28] the Survey of Labour and Income Dynamics (SLID),[29] Canadian System of National Accounts (CSNA),[30] the General Social Survey (GSS),[31] the Canadian Cancer Risk Management Model (CRMM),[32] the Survey of Employment, Payrolls and Hours (SPEH),[33] Canadian Community Health Survey (CCHS),[34] and various scientific published and grey literature sources.

BN Model

A simplified representation of the model is illustrated in Figure 2 (the full network is provided in Additional file part A). With this model we estimate the expected cost of lung cancer cases averted given different silica exposure reduction interventions. The silica reduction intervention decisions in the model include one of three interventions of WM, LEV, and PPE as well as comibinates of these them, as follows: WM-LEV-PPE, WM-LEV, WM-PPE, LEV-PPE, gives rise to seven different silica exposure reduction possibilities (represented by rectangles). In the BN, to demonostrate the uncertainty related to each domians, we use random variables (represented by ellipses). A random variable can assume more than one value due to the chance (e.g. sex of lung cancer cases is a variable with two values, i.e., male and female that each value has a probability of occurrence). In our model, the random variables related to the lung cancer case

costs are age, sex, survival rate, direct costs of lung cancer cases, annual wage of workers and monetary value of a quality-adjusted life year (QALY). The random variables related to the interventions cost are the number of silica-exposed workers in the construction sector, silica exposure level, intervention's effectiveness, coverage and intervention unit cost. Implementation of each of these interventions bares on the intervention costs, the exposure reduction experienced by workers, and in the long run, on the total number of cases and related costs averted. BN use utility nodes for estimation of the expected costs and benefits of the decision to be made (represented by hexagons). These two types of nodes (i.e., decision nodes and utility nodes) enhance the BN to decision support tool to determine the decision to make, which gains the highest expected utility, considering the given circumstances.[21,23] Additional file part B lists variables definition, distribution and data sources.

"INSERT Figure 2 HERE"

*Number of silica-exposed workers and level of exposure.*We estimate the number of the silica-exposed workers in the Ontario, Canada construction sector as about 91 thousand, based on estimates from OCRC Canada.[24] (exposed occupations listed in Additional file part C). We also identify the level of silica exposure among construction workers into three ranges: low (< 0.0125 mg/m^3), medium (0.0125- 0.025 mg/m^3), and high (> 0.025 mg/m^3), with probabilities of 0.47, 0.39, and 0.14, respectively, based on occupational exposure data sources from CAREX Canada.[25]

Intervention's effectiveness, coverage and cost. Wide ranges of effectiveness have been reported for silica exposure reduction interventions in the literature.[5–10] To be conservative, we assume the lowest reported effectiveness probability of WM, LEV and PPE are 82%[7], 93%[9], and 90%[7], respectively. We also assumed that only in 75% of the construction projects workers use interventions effectively. For a combined use of each of WM or LEV with PPE (i.e. WET-PPE, LEV-PPE), we consider the additive effects. Level of silica exposure after implementation of intervention is modelled by considering primary silica exposure and the effectiveness of each interventions (Additional file part D).

Intervention coverage represent the probability of silica-exposed workers be protected by each interventions. The coverage of WT and LEV are estimated at 0.6 and 0.4, respectively, based on the OSHA,[5] which means among all silica-exposed workers in constructions sector, only 60% and 40% can be protected by WT and LEV, respectively (Additional file part E). We assume PPE is applicable to all construction occupations.

Intervention costs are estimated by using three variables: 1) number of the silica-exposed workers that are protected by intervention, 2) intervention unit cost and 3) intervention protection factor, as indicates in expression 1. For estimation of the unit cost of the WM, LEV, and PPE, we use OSHA[5] (Additional file part F). Protection factor represents number of silica-exposed workers that can be protected by each unit of WM or LEV. Recall, WM and LEV protect a group of workers, so for estimation of the total cost of these interventions, we need to know how many workers are protected by each unit of them. For estimation of

the protection factor of WM and LEV we drew from Lahiri et al.[7] and estimates its average at 5 workers, and assume it ranging from 1 to 10 workers with Gaussian distribution. Note that PPE total cost does not depend on the protection factor, as each unit of PPE only protect one silica-exposed worker.

[Due to technical limitations, this equation is only available as a download in the supplemental files section.]

*Lung cancer cases age, sex, survival.*We define the age occupational lung cancer cases in 13 intervals, ranging from 25 to more than 85 years of age.[24] The highest probability of lung cancer is in the age of 70–74. This older age of onset is due to the long latency of this disease (Additional file part G). Additionally, men have a higherincidence of occupational lung cancer than women (0.7 versus 0.3) because of their higher level of exposure in different male-dominated occupations in the construction sector.[24] We identified the survival probability of lung cancer cases at 0.09 from CRMM.[32]

Annual wage of workers. To estimate average labour-market earnings of workers for each age and sex group, we used LFS,[28] and SLID.[29] Then we add 14% to account for payroll cost paid by employers, based on employer contribution data from the CSNA.[30] We define labour-force participation following treatment of lung cancer cases at 0.77, similar to Earle et al.[35] It is assumed that once they returned to work, their productivity is the same as the productivity of the general population.

*Monetary value of a quality-adjusted life-year.*Given the wide range of monetary values of a QALY in the health economics literature, we consider a range of value in the form of sensitivity analyses. Our baseline value is $150,000 which is reflective of willingness-to-pay values for a QALY identified in recent studies.[36] For sensitivity analyses we use a range from $100,000, which has been used in Canada in the health technology assessment field, to $200,000 which has been extrapolated from increases in health care spending over time and the health gains that have been associated with those increases.[37]

*Lung cancer cases.*Number of the lung cancer that expected to be induced in different level of silica exposure, estimated by using two variables of number of the silica-exposed workers that are protected by each intervention, and the probability of lung cancer, as described in expressions 2. The number of the silica-exposed workers that are protected by each intervention depends on the intervention coverage that described above. We estimate the probability of lung cancer for different level of silica exposure ranges from low, medium, and high at 9.1E–04, 1.2E–03, and 1.4E–03, respectively, based on OCRC.[24] (Additional file part H). After the implementation of each intervention, silica exposure is reduced to a lower level, depending on the effectiveness of the intervention (e.g. by using PPE the level of silica exposure shift from medium to low) and consequently, we expect a lower probability of the lung cancer among the protected group of silica-exposed workers. In the expression, x is the silica exposure reduction interventions, which can take WM, LEV, PPE, or combination of them.

$$\text{Lung cancer cases}_{(x)} = \text{number of the workers protected}_{(x)} \times \text{probability of lung cancer}_{(x)} \quad (2)$$

Lung cancer direct, indirect and intangible costs. These are three sub-categories of the economic burden of lung cancer cases, which are estimated based on our previous study.[16] We draw direct cost of lung cancer into three categories: healthcare,[32] out-of-pocket costs,[38] and informal caregiving costs,[39] and assume it follow a Gaussian distribution.[40] We calculate output/productivity losses and home production losses of lung cancer cases under the indirect cost and monetary value of health-related quality of life losses of lung cancer under the intangible cost category. We considered monetary value of time lost due to poor health or premature death using survival probabilities from the Canadian population.[16] The description of used techniques to estimate theses costs, are presented in Additional file part I.

Results

Expected Costs and Benefits

Table 1 presents the expected lung cancer cases averted and net benefit of the seven silica expsoure reduction interventions. The values are calculated separately for each of the seven interventions combination. The percentage of the silica-exposed workers assume to be protected by each intervention, and the expected lung cancer cases averted are indicated in the first and the second rows, respectively. In the table, we illustrate the cost of lung cancer cases averted (i.e. the benefit) with a positive sign and the intervention costs with a negative sign. As indicates in Table 1, we find the highest lung cancer cases are averted with a combined use of WM, LEV and PPE, about 107 cases, and the net benefit to be $45.9 million. In this intervention, all the silica-exposed workers are simultaneously protected with a combined use of the three methods, which makes the cost of this intervention the highest amongst the seven interventions.

With simultaneous use of WM and LEV, about 95 lung cancer cases are expected to be averted. In this intervention, all silica-exposed workers are protected with either WM or LEV. The net benefit of this intervention is about $106.6 million, which is the highest among the seven interventions. The implementation cost of this intervention is much less than the cost of the combined use of all three methods, which makes it a more desirable intervention in the case of budget restrictions.

In the case of WM-PPE or LEV-PPE use, we expect a similar number of lung cancer cases averted, about 102 and 101 cases, respectively. With these interventions all silica-exposed workers are protected by PPE, but only a percentage of them are protected by WM or LEV. For example, in WM-PPE, 60% of the silica-exposed workers are protected by both WM and PPE and the remainder are protected with PPE, while for LEV-PPE only 40% of all silica-exposed workers are protected by both LEV and PPE. The net benefit of WM-PPE is estimated at $52.8 million, which is much lower than LEV-PPE, at about $77.2 million, due to its higher intervention cost.

With PPE use alone, we expect 96 lung cancer cases averted and a net benefit estimate of $85.3 million. The results indicate that lung cancer cases averted with PPE are relatively higher than WM and PPE

controls on their own. However, the total benefit of this intervention is lower than WM and PPE, due to a higher implementation cost.

The lung cancer cases averted with WM and LEV on their own are estimated at 57 and 42 cases, respectively, which is relatively lower in comparison other intervention options, as they only protect a percentage of the silica-exposed workers (i.e., 60% in WET and 40% in LEV). The net benefit of WM is estimated about $52.8 million, which is slightly lower than LEV, at $53 million, due to its higher intervention cost.

The benefit-cost ratio of all seven interventions are positive. The highest benefit-cost ratio is achieved with LEV (4.4), followed by combined use of WM and LEV (2.9), WET (2.2), PPE (2.1), LEV-PPE (1.8), WET-PPE (1.4), and WM-LEV-PPE (1.3). The general rule of thumb is that if the benefit is higher than the cost the project is a good investment. Although it is important to note this fact, WM and LEV on their own protect only a percentage of silica-exposed workers.

“INSERT Table 1 HERE”

Sensitivity Analysis

Table 2 shows how the number of silica-exposed workers and the level of exposure affect on the net benefit of each of seven silica exposure reduction interventions. We set the level of exposure at low, medium, and high exposure and estimate the net benefit of the interventions, for the lower to upper bound values of silica-exposed workers in the construction sector. With a combined use of the three types of controls, we expect a net benefit of $4 million when we set silica-exposed workers and level of exposure at the lower bound value, while we expect net benefit of $107 million when at upper bound value. With WM and LEV combined and PPE on its own, we expect a net benefit of $60 million and $45 million, respectively, when we set silica-exposed workers and level of exposure at the lower bound, while we expect net benefit of $101 million and $94 million respectively when we set it at the upper bound. Note that WM and LEV combined and PPE on its own both protect 100% of exposed workers.

“INSERT Table 2 HERE”

Discussion

Among the seven silica exposure reduction interventions considered in this study, we estimate the highest number of lung cancer cases are averted with a combined use of WM-LEV-PPE (107 cases). Despite this fact, the highest net benefit is achieved with WM and LEV, about $106.6 million, due their lower implementation costs. The lowest number of lung cancer cases are averted with WM or LEV (55 and 40 cases), as these interventions protect only a fraction of the silica-exposed workers. With a low or medium level of silica exposure, a combined use of WM and LEV are expected to produce a highest net benefit,

while with a high level of exposure, the combined use of WM-LEV-PPE is expected to result in a highest net benefit.

One potential use of BN model is trade-off analysis between expected costs and benefits of an intervention when there is a budget constraint, or when one is interested in identifying the required budget to avert a specific number of lung cancer cases. For example, as shown in Table 1, we can consider a situation in which the budget is constrained to $70 million. In such a situation, using WM-LEV is the only intervention that will protect 100% of silica-exposed workers without the total intervention cost exceeding the pre-set amount. Trade-off analysis provides an opportunity for decision-makers to define their targets regarding the prevention of a specific number of occupational lung cancer cases, considering the existing budget.

To our knowledge, this is the first study to exclusively consider the cost of silica-related occupational lung cancer cases averted as the benefit of intervention. Therefore, it is difficult to compare our findings with those of other studies. For example Lahiri et al.[7] consider the averted cost of occupationally induced silicosis as a benefit and introduce different interventions as the preferred cost-effective intervention with a ratio (i.e., dollars per healthy years gained) vary between $132.3 ($105.9 in 2011 US dollars) and $136.2 ($109 in 2011 US dollars) for different geographic sub-regions. However, they do not include cost items such as healthcare, informal caregiving, out-of-pocket, and home production losses in their analysis. Despite the difference in economic evaluation methodologies and inconsistencies of considered outcomes, our results are in line with Lahiri et al.[7], as we also identify the net benefit of WM-LEV as the highest among seven interventions. However, as they neither report the average per-case cost for interventions nor the number of silica-exposed workers affected, we are unable to estimate per-case value for their study.

In another study in the United States, OSHA estimates the net benefit of compliance with the new silica rule in terms of reduction of cost of silica-related diseases (i.e., fatal cases of lung cancer, non-malignant respiratory disease, renal disease and nonfatal cases of silicosis).[5] They estimate the net annualized benefit of a reduction in the acceptable limit of exposure to be between $2.4 billion and $9.9 billion ($1.8 billion and $7.5 billion in 2009 US dollars), with a midpoint value of $6.1 billion ($4.6 billion in 2009 US dollars). The lower exposure limits annually prevent 688 fatalities (567 fatalities in the construction sector) and 1,585 moderate-to-severe silicosis cases (1,080 cases in the construction sector).

While the BN model developed in this study can support decision making, in its current form there is room for improvement of the approach. Future study directions ought to include further research on the expansion of the model contents, including consideration of a broader set of variables. In our study, the benefits side of our economic evaluation is limited to occupational lung cancer cases averted, despite the fact, there are several other silica-related occupational diseases such as silicosis and silicosis-related disease.[4–5,7] Furthermore, our model structure can be improved by considering a greater number of relationships between the key variables as, we ignored some interactions because of limitations in background knowledge. For instance, interventions may adversely influence labour and/or equipment

productivity[5] and under certain circumstances health-related quality of life of workers affected by the intervention.[17] A more comprehensive analysis would consider other variable interactions that are caused by implementing an intervention. Lastly, in this study we did not investigate the trend of lung cancer cases reduction after implementation of the intervention. Undoubtedly, ultimate effect of intervention can only be revealed after several years. Further research is needed to estimate how many years after intervention reduction of lung cancer cases reach to its steady state.

Conclusions

This study is one of the first to apply Bayesian network, as probabilistic modeling approach, in the occupational health and safety intervention economic evaluation, and provides an overview of the potential advantages of probabilistic modeling approach, in particular when the decision contexts contains a large number of uncertain variables. Thus, this study is useful for researchers who are dealing with substantial levels of uncertainty in their economic evaluations. Results indicate that, among seven silica exposure reduction interventions, the highest number of lung cancer cases are averted with a combined use of WM-LEV-PPE, but the highest net benefit is achieved with WM-LEV. Results also suggest that the level of exposure is an important determinant for selection of the most cost-beneficial intervention. Considering the increasing attention being focused on the prevention of occupational cancer, we anticipate the case study provides important insights for decision makers about silica exposure reduction interventions in the construction sector.

Declarations

Ethics approval and consent to participate

Not applicable. All input data in this study drawn from publicly available data sources.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analysed during this study are included in this published article and supplementary information file.

Competing interests

Not applicable.

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Authors' contributions

AM: Lead author of this study. Led the conceptual and methodological design of probabilistic analysis and economic component of the study. ET: Study co-investigator. oversight the conceptual and methodological design of the economic component of the study, assisted in preparing the manuscript write-up, reviewed drafts of the manuscript and provided editorial suggestions. SM: Study co-investigator. Contributed to the methodological design and oversight on technical aspects of occupational hygiene component. AE: Study co-investigator. Contributed to the conceptual and methodological design of probabilistic modeling component of the study, reviewed drafts of the manuscript and provided editorial suggestions. PD: Project team lead. Led the conceptual and methodological design of the epidemiological component of the study, reviewed drafts of the manuscript and provided editorial suggestions. All authors have participated in the conception and writing of this manuscript and have read the final version of the manuscript. The manuscript represents honest work.

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Abbreviation

WM: Wet method; LEV: Local exhaust ventilation; PPE: personal protective equipment; OSHA: Occupational Safety and Health Administration; BN: Bayesian network; OCRC: Occupational Cancer Research Centre; LFS: Labour Force Survey; SLID: Survey of Labour and Income Dynamics; CSNA: Canadian System of National Accounts, GSS: General Social Survey; CRMM: Canadian Cancer Risk Management Model; SPEH: Survey of Employment, Payrolls and Hours; CCHS: Canadian Community Health Survey; QALY: Quality-Adjusted Life Year; CCO: Cancer Care Ontario.

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Tables

Table 1. Expected Costs and Benefits of Silica Exposure Reduction Interventions

Intervention (Yes=component implemented; No=component not implemented)	WM= Yes				WM= No		
	LEV= Yes		LEV= No		LEV= Yes		LEV= No
	PPE=Yes	PPE=No	PPE=Yes	PPE=No	PPE=Yes	PPE=No	PPE=Yes
Protected workers[a]	100%	100%	100%	60%	100%	40%	100%
Lung cancer cases averted[b]	107	95	102	55	101	40	96
Averted costs (benefits)							
Direct	$9.5M	$8.4M	$9.0M	$4.9M	$8.9M	$3.5M	$8.6M
Indirect	$41.2M	$36.6M	$39.3M	$21.1M	$38.8M	$15.3M	$37.1M
Intangible	$133.9M	$119.1M	$127.6M	$68.6M	$126.0M	$49.7M	$120.7M
Total	$184.5M	$164.2M	$175.9M	$94.5M	$173.8M	$68.5M	$166.4M
Intervention costs							
WM[c]	-$42.0M	-$42.0M	-$42.0M	-$42.0M	$0	$0	$0
LEV[d]	-$15.5M	-$15.5M	$0	$0	-$15.5M	-$15.5M	$0
PPE[e]	-$81.1M	$0	-$81.1M	$0	-$81.1M	$0	-$81.1M
Total	-$138.6M	-$57.6M	-$123.1M	-$42.0M	-$96.6M	-$15.5M	-$81.1M
Net benefit[f]	$45.9M	$106.6M	$52.8M	$52.5M	$77.2	$53.0M	$85.3M
Benefit to cost ratio[g]	1.3	2.9	1.4	2.2	1.8	4.4	2.1

Note. *[a]Percentage of the silica-exposed workers in construction sector that are protected by each intervention, [b]expected number of the occupational lung cancer cases averted, [c]total cost of implementing WM, [d]total cost of implementing LEV, [e]total cost of implementing PPE, [f]difference between cost of lung cancer cases averted and cost of intervention, [g]calculated by dividing the total benefits by the total costs of an intervention. Due to rounding, columns, and rows may not sum to 100%, All table monetary values are in 2017 Canadian dollars.*

Table 2. Sensitivity Analysis of Interventions for Different Numbers of Silica-Exposed Workers and Different Levels of Exposure

	Baseline	Low Exposure (<0.0125 mg/m^3)		Medium Exposure (0.0125- 0.025 mg/m^3)		High Exposure (>0.025 mg/m^3)	
		Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound
Silica-exposed workers[a]	91	46	118	46	118	46	118
No Intervention							
Expected LC cases[b]	110	60	111	80	140	95	180
Total LC costs[c]	$189M	$103M	$191M	$138M	$241M	$164M	$310M
WM, LEV, PPE							
LC cases averted[d]	107	60	111	79	138	84	162
Total LC costs averted[e]	$185M	$103M	$191M	$136M	$238M	$145M	$280M
Total intervention costs[f]	$151M	$99M	$173M	$99M	$173M	$99M	$173M
Net benefit[g]	$46M	$4M	$19M	$37M	$65M	$46M	$107M
Net benefit change (%)	-	10%	41%	80%	142%	100%	233%
WM, LEV							
LC cases averted[d]	95	60	111	71	124	46	100
Total LC costs averted[e]	$164M	$103M	$191M	$122M	$214M	$79M	$172M
Total intervention costs[f]	$63M	$43M	$71M	$43M	$71M	$43M	$71M
Net benefit[g]	$107M	$60M	$120M	$79M	$143M	$36M	$101M
Net benefit change (%)	-	57%	113%	74%	134%	34%	95%
Only PPE							
LC cases averted[d]	96	59	109	73	129	57	113
Total LC costs averted[e]	$166M	$101M	$187M	$126M	$222M	$97M	$195M
Total intervention costs[f]	$81M	$56M	$101M	$56M	$101M	$56M	$101M
Net benefit[g]	$85M	$45M	$86M	$70M	$120M	$42M	$94M
Net benefit change (%)	-	53%	101%	83%	141%	49%	110%

Note. *[a]number of the silica-exposed workers in the construction sector in thousand, [b]expected occupational lung cancer cases, [c]total cost of occupational lung cancer cases with no intervention, [d]expected occupational lung cancer cases averted after implementation of an intervention, [e]total cost of lung cancer cases averted, [f]cost of implementing a silica exposure reduction intervention, [g]difference between cost of lung cancer cases averted and cost of intervention. All table monetary values are in 2017 Canadian dollars.*

Figures

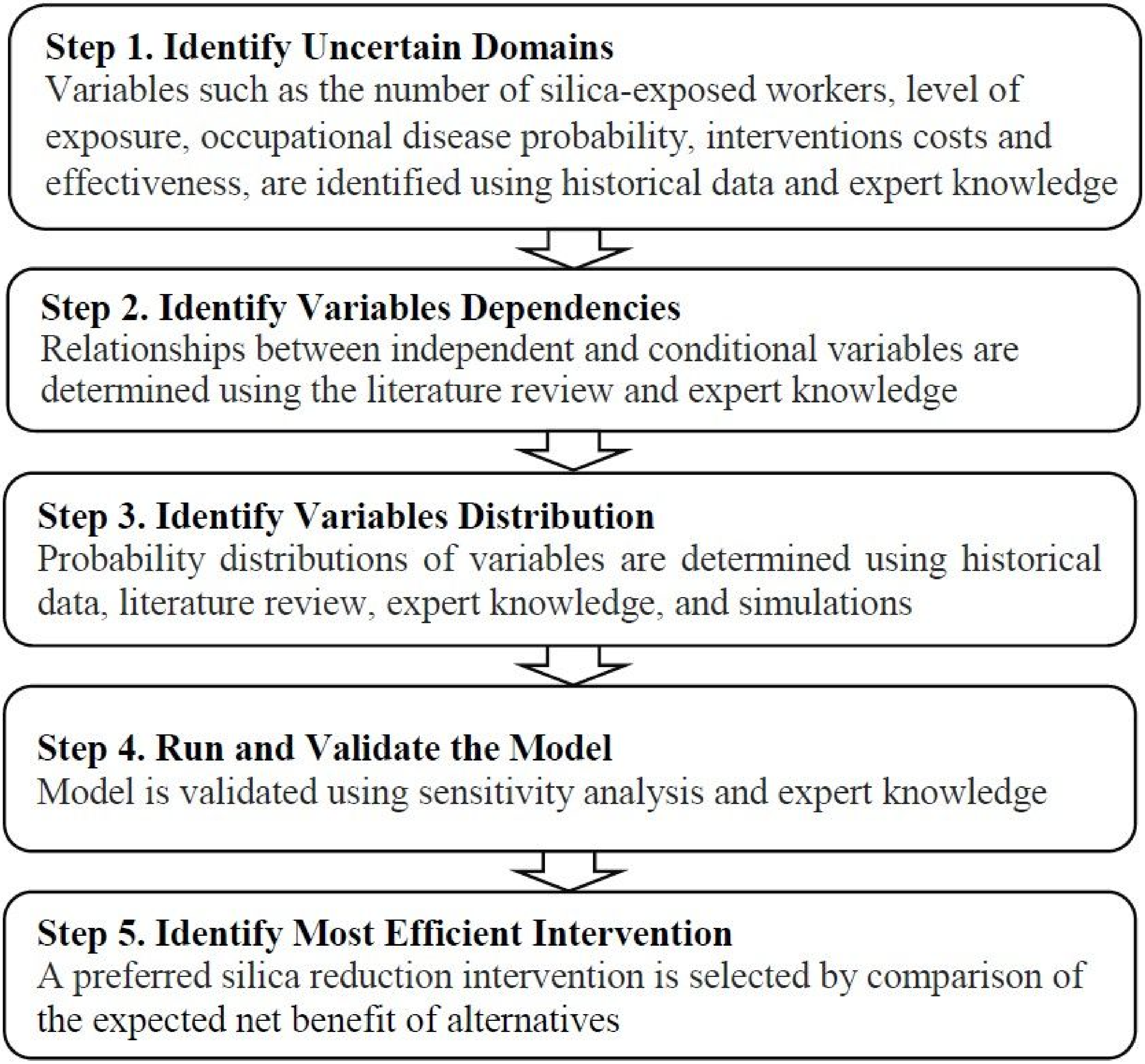

Figure 1

Steps of a Probabilistic Modeling Approach for Economic Evaluation of Silica Exposure Reduction Interventions

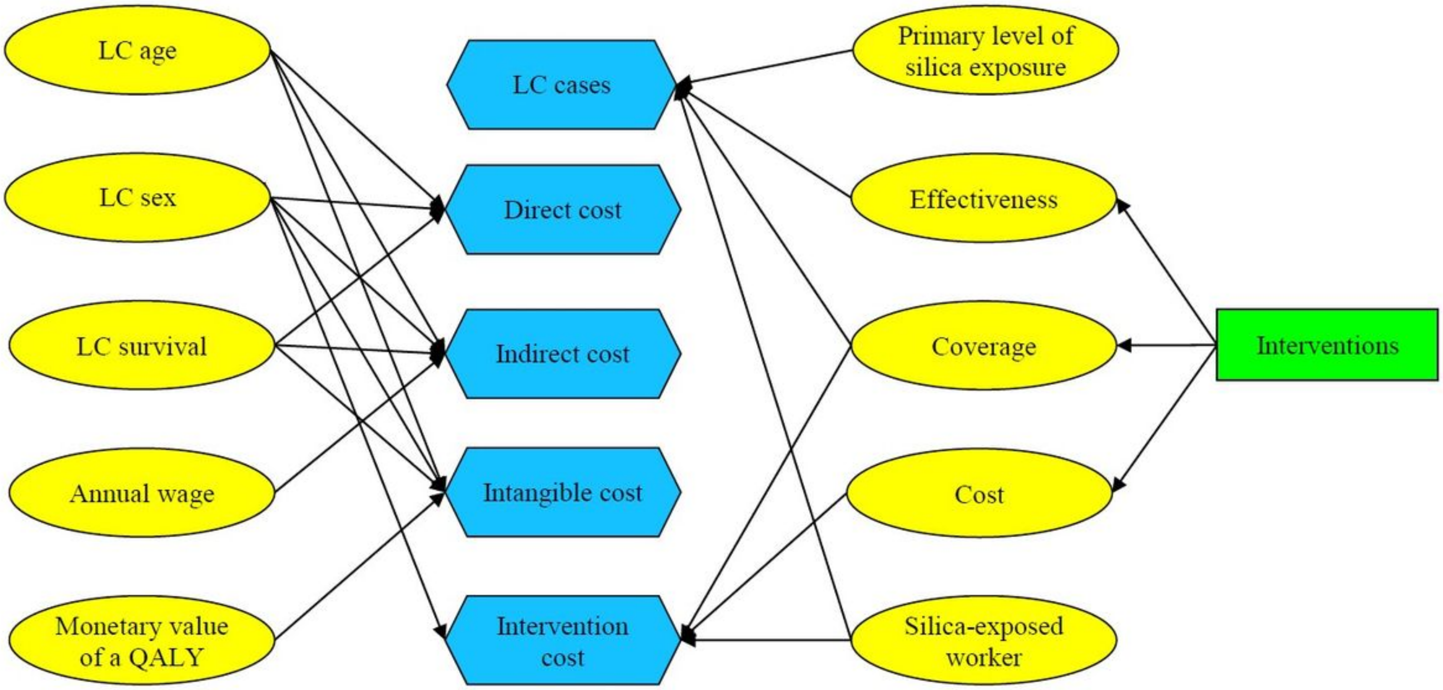

Figure 2

A Simplified Representation of Economic Evaluation Model of Silica Exposure Reduction Interventions, Using Bayesian Network

Supplementary Files

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