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Development of a lower back pain prevention index for heavy equipment operators in the construction industry: system dynamics modelling

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ABSTRACT

Lower back pain (LBP) due to the whole-body vibration exposure is a common health problem among heavy equipment operators in the construction industry. This study utilizes a system dynamics modelling approach to develop a dynamics model of the LBP prevention index in Sri Lankan construction industry to assess the current level of LBP prevention maturity and plan for long-term improvement. The developed dynamics model consists of five key factors, namely (1) personal, (2) organizational, (3) equipment, (4) job-related and (5) social-context, together with their 17 associated items. Both secondary and primary data are used for the model development. Secondary data are extracted from several literature reviews, while primary data are obtained from interviews and observations on sites. The simulation results show that the LBP prevention index reaches the highest maturity level, which is level 5, at 39 years. Personal, job-related and social-context are key factors that enhance the LBP prevention index in the long-term. A construction company should focus more on human aspects than equipment acquisition, as this helps to achieve higher levels of maturity in the long-term. A construction company can use the developed dynamics model to plan for an effective LBP prevention program to enhance the LBP prevention index in the long-term.

KEYWORDS

Construction industry; heavy equipment operator; lower back pain; system dynamics modelling; whole-body vibration exposure

Introduction

Prolonged exposure to whole-body vibration (WBV) is a major health hazard among heavy equipment operators (HEOs) in the construction industry (Gillin et al. 2006). Vitharana et al. (2014) stated that WBV exposure level of the HEOs exceeds the limit set by the ISO 2631-1 Standard. Prolonged exposure to WBV damages peripheral and autonomic nerves. Prolonged exposure also damages vestibular, vascular, digestive and female reproductive systems and causes lower back pain (LBP) (De Beeck & Hermans 2000; Bovenzi 2005).

Most HEOs experience LBP due to WBV exposure (Bovenzi 2005; Langer et al. 2012). It is a major disability and therapeutically challenging pain condition, and is a major cause of compensation claims, sick leaves and early retirement (McPhee et al. 2001; Shinozaki et al. 2001; Shraim et al. 2015). Many countries identify the LBP due to WBV exposure as a compensation-qualifying occupational disease (Paschold and Mayton 2011). According to Waters et al. (2008), the risk of LBP development among the HEOs is twice that of other construction workers.

Many research studies have been conducted in the area of LBP due to WBV exposure. Tamrin et al. (2007), for example, utilized logistic regression analysis to examine a combination of risk factors, such as age, weight and education level affecting LBP due to WBV exposure among bus drivers in Malaysia. Tiemessen et al. (2007) examined various strategies to decrease LBP due to WBV exposure, and concluded that equipment provisions and worker skills are crucial to reduce the pain. Yassierli (2017) suggested that LBP-related training and job rotation help reduce sick leaves in a company.

The above research presents insights into LBP due to WBV exposure, but do not capture causal relationships among key LBP-related factors, and their interactions over time. There is also a need for construction companies to develop some strategies to reduce LBP, and examine areas for long-term improvement. Such actions are essential, as they add values to a company, and reduce unnecessary costs that might occur in the long term. This research study, therefore, develop a dynamics model of the LBP prevention index for the HEOs utilizing a system dynamics (SD) modelling approach. Key factors affecting LBP due to WBV exposure and their

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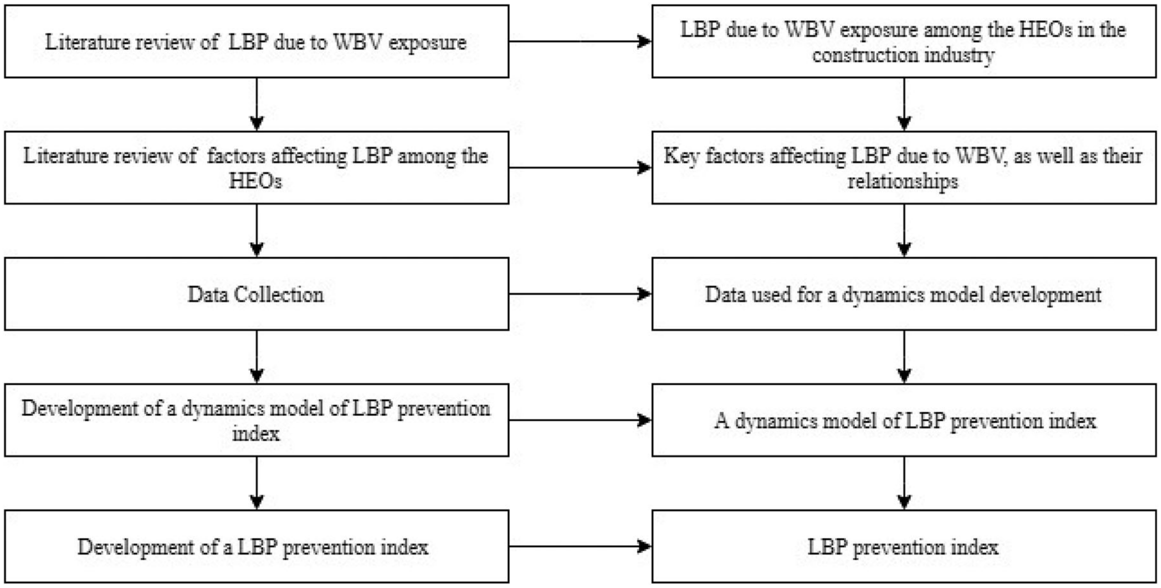

Figure 1. Research steps of the study.

interrelationships are used to develop the dynamics model. The study results enhance the understanding of LBP due to WBV exposure and can guide an effective LBP prevention program in the long-term.

Methodology

The steps of this research study are as shown in Figure 1. A comprehensive literature search is performed to better understand LBP due to WBV exposure and its effects on workers' health. A list of factors affecting LBP due to WBV exposure among HEOs and their interrelationships are summarized and used to develop dynamics model. Both secondary and primary data are used to develop equations for the dynamics model. Secondary data are obtained from several papers, such as vibration level, training cost, and seat and machine costs. Primary data are collected through interviews and observations on construction sites in Sri Lanka. Interviews are conducted with project engineers, project managers and executives to gain perceptions of policies, strategies and regulations related to health and safety in a company. HEOs are also interviewed to gain personal-related information, such as weight, working experience and work behaviour. The developed dynamics model is then used to achieve the LBP prevention index. This index is used, together with the LBP prevention maturity levels, to assess the current maturity level of a construction company. Factors with low performances are pinpointed and planned for improvement, to achieve higher index score in the long-term.

Factors and their associated items affecting LBP due to WBV exposure

Many studies have been conducted to identify the factors affecting LBP due to WBV exposure. Jack and Oliver (2008), for example, examined the chances of having musculoskeletal problems among operators in the forestry industry, and concluded that the work duration, WBV exposure and equipment condition are the key criteria of musculoskeletal problems. Mohseni-Bandpei et al. (2011) utilized a structured questionnaire to conclude that the, personal and job-related factors are crucial in preventing LBP among surgeons in Iran. Ramond-Roquin et al. (2015) employed multistep logistic regression modelling to the examined risk factors affecting LBP among French male workers, and summarized four potential risk factors, including (1) biomechanical, (2) organizational, (3) psychosocial and (4) individual factors.

Vitharana and Chinda (2017) utilized a structural equation modelling approach to examine the key factors affecting LBP due to WBV exposure and their interrelationships in the Sri Lankan construction industry. They concluded that there are five key factors: (1) personal (PNF), (2) organizational (ORF), (3) equipment (EQF), (4) job-related (JRF) and (5) social-context (SCF) factors with a total of 17 associated items (see Table 1). The PNF, JRF and SCF factors consist of three items each, while the ORF and EQF factor are associated with four items each. Ramond-Roquin et al. (2015) mentioned that the chances of having LBP for senior workers are higher than that for young workers (an item under the PNF factor). Night shift work (an item under the JRF factor) causes a high chance of

Table 1. Factors and items affecting LBP due to WBV exposure (Vitharana and Chinda 2017).

Factor	Item	Description	Source
Personal (PNF)	1. Age of the worker (AOW)	Chances of having LBP are high for old-aged workers	Ramond-Roquin et al. (2015), Mok et al. (2016), Vitharana and Chinda (2016)
	2. Weight of the worker (WGT)	Overweight and underweight workers experience high chances of having LBP	
	3. Working hours (WHO)	Long working hours associated with higher chances of having LBP	
Organizational (ORF)	1. Health and safety budget (SBT)	Adequate provisions of the health and safety budget for LBP-related activities help in reducing chances of having LBP	Hartvigsen et al. (2004), Lionel (2014), Yang et al. (2016)
	2. Training program (TPM)	Provisions of LBP-relating training help to reduce the chance of having LBP	
	3. WBV standard (VST)	Several WBV standards focus on reducing WBV exposure level	
	4. Working experience (WEP)	Experienced workers have less chances of having LBP	
Equipment (EQF)	1. Seat type (STP)	Proper seats reduce WBV exposure level	Hartvigsen et al. (2004), Kittusamy and Buchholz (2004), Blood et al. (2010)
	2. Age of the machine (AOM)	Obsolete machines have high WBV exposure level	
	3. WBV exposure (VEX)	High WBV exposure level causes LBP	
	4. Soil type (SOT)	Different soil types have different WBV exposure levels	
Job-related (JRF)	1. Night shift (NSF)	Night shift work is associated with LBP	Mendelek et al. (2011), Mok et al. (2016) Yang et al. (2016)
	2. Job rotation (JOR)	Rotating jobs assist in reducing chances of having LBP	
	3. Exercise(EXR)	Exercise helps to reduce the chance of having LBP	
Social context (SCF)	1. Job satisfaction (JOS)	Workers who have high satisfaction level have less chance of having LBP	Hartvigsen et al. (2004), Mendelek et al. (2011), Mohseni-Bandpei et al. (2011)
	2. Smoking (SMK)	Chances of having LBP are higher among those who smoke	
	3. Education (EDU)	Educated workers tend to have less chance of having LBP	

having LBP. The chance of having LBP among smokers is higher than for those who do not smoke (an item in under the SCF factor). Ergonomic-related training (an item under the ORF factor) and ergonomic-related equipment (an item under the EQF factor) assist in reducing the chances of having LBP.

The relationships among the five key factors affecting LBP due to WBV exposure are also examined using the structural equation modelling approach (see Figure 2) (Vitharana and Chinda 2017). The ORF factor is an important factor, as it supports the implementation of the other four factors, directly and indirectly. An adequate health and safety budget (an item under the ORF factor) assists in acquiring LBP-related equipment (an item under the EQF factor), training workers with LBP-related programs (an item under the ORF factor), and hiring additional workers to diminish long working hours (an item under the PNF factor). The PNF factor is also a significant factor, as it strongly affects the EQF, JRF and SCF factors. For example, proper working hours (an item under the PNF factor) reduce the chances of having LBP due to WBV exposure (an item under the EQF factor), leading to higher job satisfaction (an item under the SCF factor) (Kim et al. 2016).

In addition to the direct effects that the five key factors have on each other, the indirect effects are also crucial. The ORF factor, for example, indirectly influences the SCF and JRF factors through the implementation of the PNF factor. Providing more in the health and safety budget (SBT) (an item under the ORF factor) to hire additional workers helps to reduce the work pressure and working hours (WHO) (an item under the PNF factor), leading to higher job satisfaction (an item under the SCF factor).

This study utilizes five key factors and their causal relationships summarized by Vitharana and Chinda (2017) to develop a dynamics model of the LBP prevention index.

SD modelling

Several methods, such as regression analysis, artificial neural network, SD modelling and genetic algorithm can be used to assess health-related problems. Hallner and Hasenbring (2004), for example, applied an artificial neural network to examine the risk of LBP development in Germany. Glombiewski et al. (2010) utilized regression analysis to predict depression among back-pain patients in Germany. Sapna et al. (2012) utilized a genetic algorithm to predict diabetes. Campbell et al. (2013) determined short- and long-term outcomes of primary LBP care service in the UK using a Cox regression analysis.

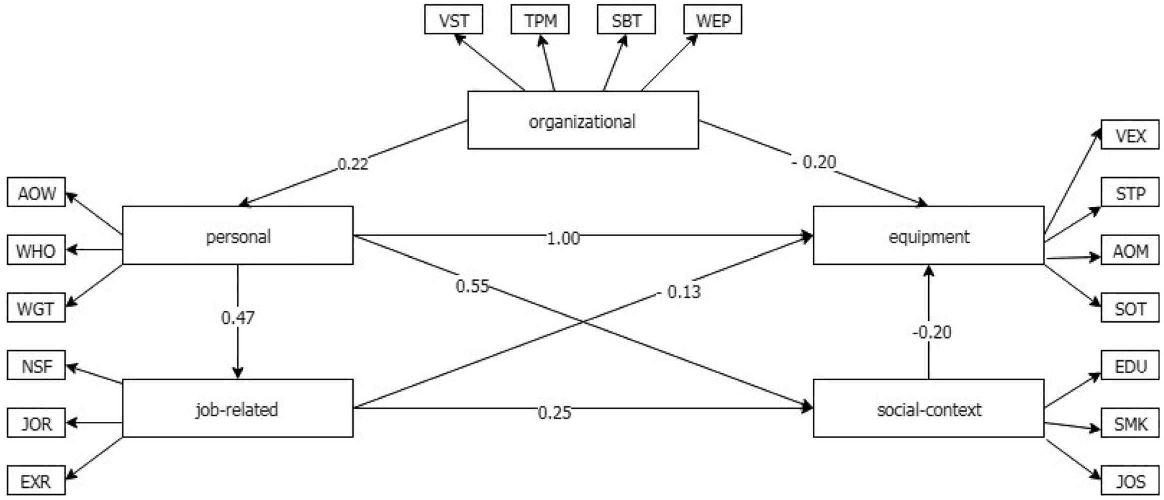

Figure 2. Interrelationships among key factors affecting LBP due to WBV exposure (Vitharana and Chinda 2017).

Table 2. Different maturity levels used in ergonomic- and health and safety-related areas.

Maturity index	Level	Score range	Area	Reference
Construction safety culture maturity index	Level 1	0–200	Construction industry	Mohamed and Chinda (2011)
	Level 2	201–400		
	Level 3	401–600		
	Level 4	601–800		
	Level 5	801–1000		
Ergonomic maturity level	Informal	0–1	Ergonomic practitioners	Vidal et al. (2012)
	Organized	1–2		
	Structured	2–3		
	Managed	3–4		
	Optimized	4–5		
Health risk management maturity index	Unknown	0–10	Construction industry	Hopkinson et al. (2015)
	Reactive	10–20		
	Compliant	20–30		
	Proactive	30–40		
	Enlightened	40–50		

In this study, a SD modelling approach is used to develop a dynamics model of the LBP prevention index. It is a simulation method to examine the structure of complex systems and their behaviours over time (Yu et al. 2015). It can be used to guide policy and system design in numerous fields. Doan and Chinda (2016) mentioned that SD can be used to deal with dynamic changes, in which a change can cause other changes over time.

The SD method is used in various research, such as business, construction, education, economy, policy, environment, medicine, urban planning and health (Yu et al. 2015). For example, Ritchie-Dunham and Galvan (1999) utilized a SD model to help managers understand the impacts of alternative national epidemics strategies. Shin et al. (2014) utilized a SD model to examine the effectiveness of safety improvement in the construction industry in Korea. Jetha et al. (2016) examined the complex relationships among individual, psychosocial and organizational factors affecting work disability and return to work, utilizing a SD model.

The above literature shows the appropriateness of the SD method to be used in this study.

Maturity levels of LBP prevention index

To assess and improve the LBP prevention index, different levels of LBP prevention maturity must be determined. A number of studies have been conducted to define different levels of maturity in ergonomic- and health and safety-related areas (see Table 2). Mohamed and Chinda (2011), for example, developed a construction safety culture maturity index, and divided the 1000 points into five maturity levels, with equal score of 200 points in each level. Vidal et al. (2012) summarized five ergonomic maturity levels, namely informal, organized, structured, managed and optimized. Hopkinson et al. (2015) developed a health risk management maturity index for a construction company with a total of five levels, in which each level contains 10 points.

Based on diverse perspectives of maturity levels, this study divides 1000 points of the LBP prevention index into five maturity levels. The details of each level are as follows.

- Level 1: This level has a score range of 0–200 points. At this level, the company does not consider LBP due to WBV exposure as a key business risk. The chances of having LBP due to WBV exposure are considered as a part of the job. There is no proper LBP-related training for the workers. There is a high potential for illegal safety practices and superficial incident investigation at this level (Foster and Hoult 2013).
- Level 2: This level has a score range of 201–400 points. At this level, the company sees LBP prevalence as a business risk, and attempts to reduce it. LBP prevention is detailed in rules, procedures, nd engineering controls. There is, however, minimum or inconsistent training provided at this level (Foster and Hoult 2013).
- Level 3: This level has a score range of 401–600 points. At this level, the company understands that the workers' involvement in the LBP prevention program is necessary. A majority of the workers accept their personal responsibilities to reduce the chances of having LBP due to WBV exposure. Appropriate training and awareness programs are also established.
- Level 4: This level has a score range of 601–800 points. At this level, LBP prevention is important in both moral and economic points of view. The company develops LBP- and WBV-related guidelines to reduce the chances of having LBP due to WBV exposure (Foster and Hoult 2013).
- Level 5: This level has a score range of 801–1000 points. At this level, the company has a sustained period without LBP incidents. Workers believe that LBP prevention is a critical aspect of their job, and considerable effort is provided to reduce the chances of having LBP (Foster and Hoult 2013).

The above five levels of maturity are used, together with the LBP prevention index, to assess the current level of LBP prevention maturity of a company, and plan for index improvement in the long-term.

Causal loop diagram of 17 items affecting LBP due to WBV exposure

According to Bouloiz et al. (2013), a major step of a SD model is to develop a causal relationship diagram. The diagram shows whether the relationship between each pair of variables is positive or negative, that is, if the influence of one variable on another is amplifying (positive influence) or stabilizing (negative influence) (Bouloiz et al. 2013). Typically, there are two components of a causal loop diagram: causal link and closed loop. A causal link consists of an element and an arrow. A positive causal link for elements 'A' to 'B' is formed when a change in element 'A' produces a similar change in element 'B', that is, if element 'A' increases, the element 'B' increases, and *vice versa*. If a change in elements 'A' to 'B' is, in the opposite direction, then the link is negative (Kirkwood 1998).

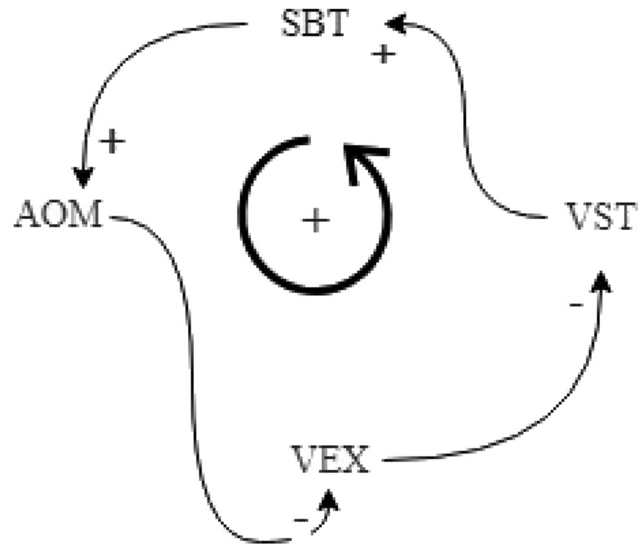

Figure 3. Example of a positive causal loop.

A causal loop is a closed sequence of causes and effects (Kirkwood 1998). A positive causal loop starts and ends in the same direction. It contains an even number of negative causal links. In contrast, if a loop starts and ends with different signs, then it is a negative causal loop and contains an odd number of negative causal links (Kirkwood 1998).

For example, with an adequate health and safety budget (SBT), a company can afford to purchase new machines (AOM) (Vitharana and Chinda 2016). This makes a positive causal link between the SBT and AOM items (see Figure 3). A new machine (AOM) reduces the WBV exposure level (VEX), reflecting a high WBV standard (VST). These represent negative links between the AOM and VEX, and the VEX and VST items (Vitharana et al. 2014). To maintain a high WBV standard, adequate budget (SBT) must be provided to improve the LBP-related activities (a positive causal link) (Blood et al. 2010). This closes the positive causal loop for the SBT, AOM, VEX and VST items.

The health and safety budget (SBT) can also be used to train (TPM) workers with LBP-related programs (Lahiri et al. 2005). This represents a positive causal link between the SBT and TPM items. Trained workers work better, gain more experience (WEP) and tend to work longer in the industry (AOW) (Lee and Tserng 2006). However, with more experiences in the work, less budget (SBT) might be provided for further training (Sawacha et al. 1999, Lahiri et al. 2005). This closes the negative causal loop for the SBT, TPM, WEP and AOW items (see Figure 4).

In this study, 17 items affecting LBP due to WBV exposure create a number of causal links and causal loops, as shown in Figure 5. They are used to develop equations in the dynamics model of the LBP prevention index.

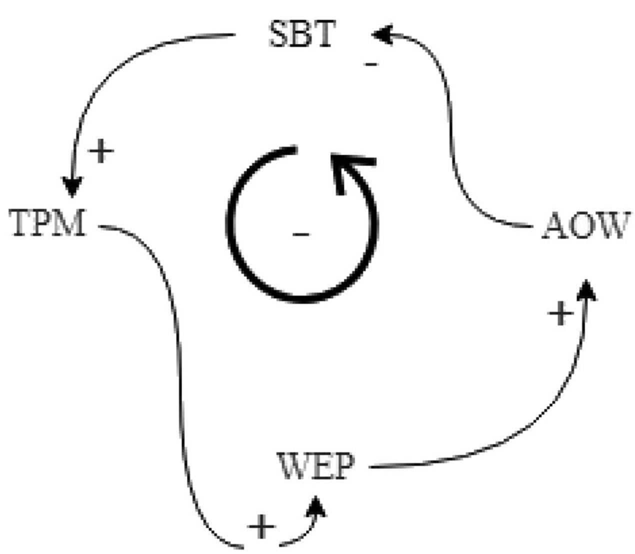

Figure 4. Example of a negative causal loop.

Data collection

Secondary and primary data are used to develop the equations for the dynamics model of the LBP prevention index (see Table 3). Secondary data are collected in the construction-, safety- and health-related literature. Vitharana and Chinda (2016), for example, mentioned that replacing heavy equipment every 10 years helps to reduce the 32.6% chance of having LBP. Alghadir and Anwer (2015) stated that workers who work less than eight hours per day have 48.8% chance of having LBP, while those who work longer hours experience a 2.4% higher chance of having LBP. Takahashi et al. (2015) claimed that night-shift workers have double the chance of LBP occurrence.

The primary data were obtained by site observations and interviews of both management and HEO positions (see Table 3). Thirty-five construction sites around Sri Lanka were observed to collect data, such as seat type, soil type and machine condition. A total of 45 managers and 105 HEOs were interviewed to gain such data as education background, working experience, training history, and health and safety budget.

The dynamics model of LBP prevention index

The dynamics model of the LBP prevention index consists of six sub-models, namely, (1) personal factor,

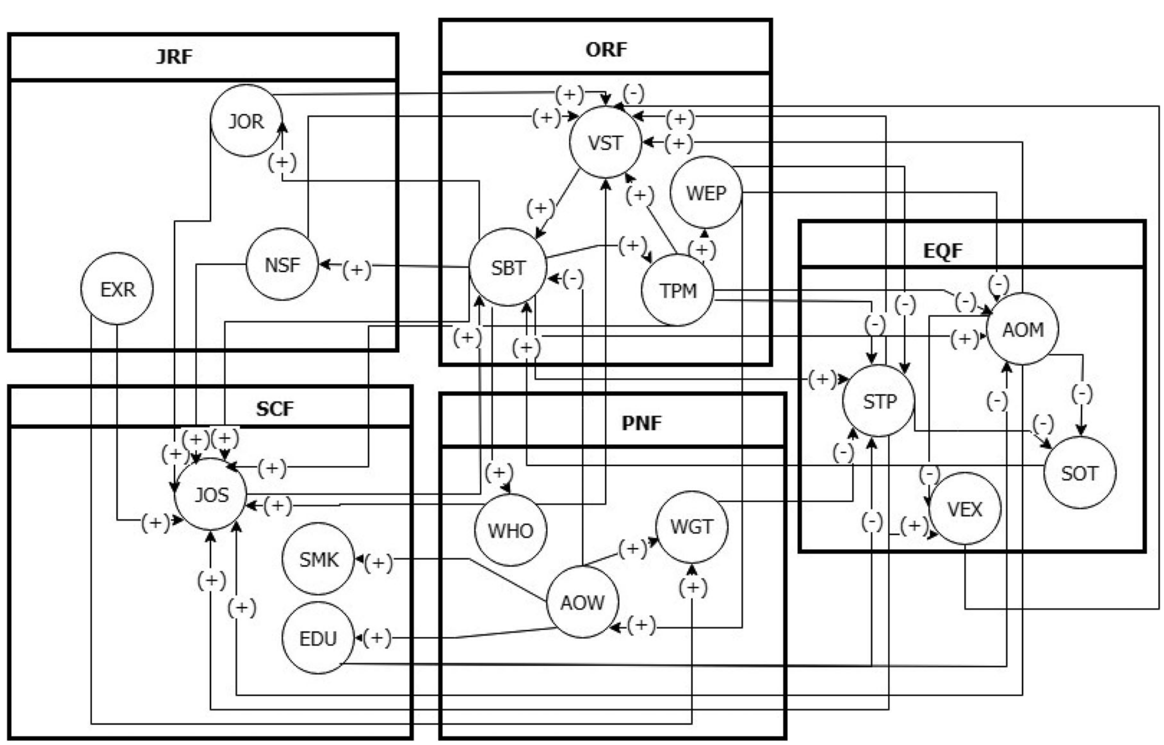

Figure 5. Causal relationships among the 17 items affecting LBP due to WBV exposure.

Table 3. Data for the dynamic model of the LBP prevention index.

Item	Description	Chance of having LBP	Reference
Personal factor			
AOW	• Young age (group A), middle age (group B), and senior (group C) experience different chances of having LBP	• Group A: 48% • Group B: 54% • Group C: 50%	Lant and Partners (2015)
WGT	• There are four different weight types in this study: underweight, normal weight, overweight and obese	• Underweight: 100% • Normal weight: 40.63% • Overweight: 50% • Obese: 58.62%	Alghadir and Anwer (2015)
WHO	• Standard working hours are eight hours per day • Many countries in South Asia, including Sri Lanka, have 12 working hours per day	• Work less than eight hours per day: 48.8% • Work more than eight hours per day: 51.2%	Alghadir and Anwer (2015)
Organizational factor			
SBT	• Health and safety budget of the construction company is approximately 5% of the total budget	–	Pellicer et al. (2014), Interview
TPM	• Different training programs are required for different age groups every three years • Training cost for groups A, B and C are 100, 127 and 100 USD per person, respectively	• Group A: 33% • Group B: 39% • Group C: 35%	Lahiri et al. (2005), Interview
VST	• The ISO 2631 Guidelines and EU Directives are used as guidelines for WBV exposure in this study	–	Paschold (2008)
WEP	• Working experience is separated into: (1) less than 10-year experience and (2) more than 10-year experience	• Less than 10 years: 55.6% • More than 10 years: 44.3%	Janwantanakul et al. (2011)
Equipment factor			
STP	• Seats used with heavy equipment are cushion and suspension seats	• Cushion seat: 63% • Suspension seat: 30.4%	Subhash and Ario (2011)
AOM	• Vibration level of the machine becomes higher after 10 years • Machine should be replaced every 10 years. • Average price of a machine is 100,000 USD	• Old machine: 63% • New machine: 30.4%	Paschold (2008), Vitharana and Chinda (2016)
VEX	• WBV exposure is affected by the AOM, JOR, NSF, STP, TPM and WHO items	–	Vitharana and Chinda (2016)
SOT	• Different soil types incur different compaction levels • Four soil types are defined, including heavy clay, silty clay, mixture of gravel and sand and clay	• Maximum chance: 63%	Rainville et al. (2004), Site observation
Job-related factor			
NSF	• Working night shift causes higher chance of having LBP	• With night shift: 42% • Without night shift: 21.5%	Takahashi et al. (2015)
JOR	• Having job rotation reduces chance of having LBP by half	• With job rotation: 40% • Without job rotation: 80%	Frazer et al. (2003)
EXR	• Exercise helps to reduce the chance of having LBP • Exercise is separated into three groups, including regular, sometimes and never exercise	• Regular: 50% • Sometimes: 70% • Never: 82%	Rainville et al. (2004)
Social context factor			
JOS	• Job satisfaction is separated into moderate, reasonable and good satisfaction	• Moderate: 34.30% • Reasonable: 25.30% • Good: 19.48%	Hoogendoorn et al. (2002)
SMK	• The prevalence of LBP is higher among the smokers	• Smoker: 57% • Non-smoker: 43%	Alghadir and Anwer (2015)
EDU	• Educational background is separated into bachelor's degree, high school and primary school	• Bachelor's degree: 41.5% • High school: 45.8% • Primary school: 64.6%	Udom et al. (2016), Interview

(2) organizational factor, (3) equipment factor, (4) job-related factor, (5) social-context factor and (6) LBP prevention index sub-models. In each sub-model, the chances of having LBP are calculated based on the items associated with that sub-model (see Figure 6). For example, the personal factor sub-model is associated with three items, namely age of the worker, weight of the worker and working hours. The chances of having LBP from the three items are calculated, and normalized to a maximum score of 1000 points, to achieve a total chance of having LBP based on the personal factor sub-model. This total chance of having LBP is used to calculate the influential scores the personal factor received from the organizational factor. The degree of influence depends on the correlation coefficient stated in Figure 2. The influential score of the personal factor sub-model is calculated by multiplying the total chance of having LBP based on the organizational factor sub-model by the correlation coefficient between the ORF and PNF factor (0.22, see Figure 2).

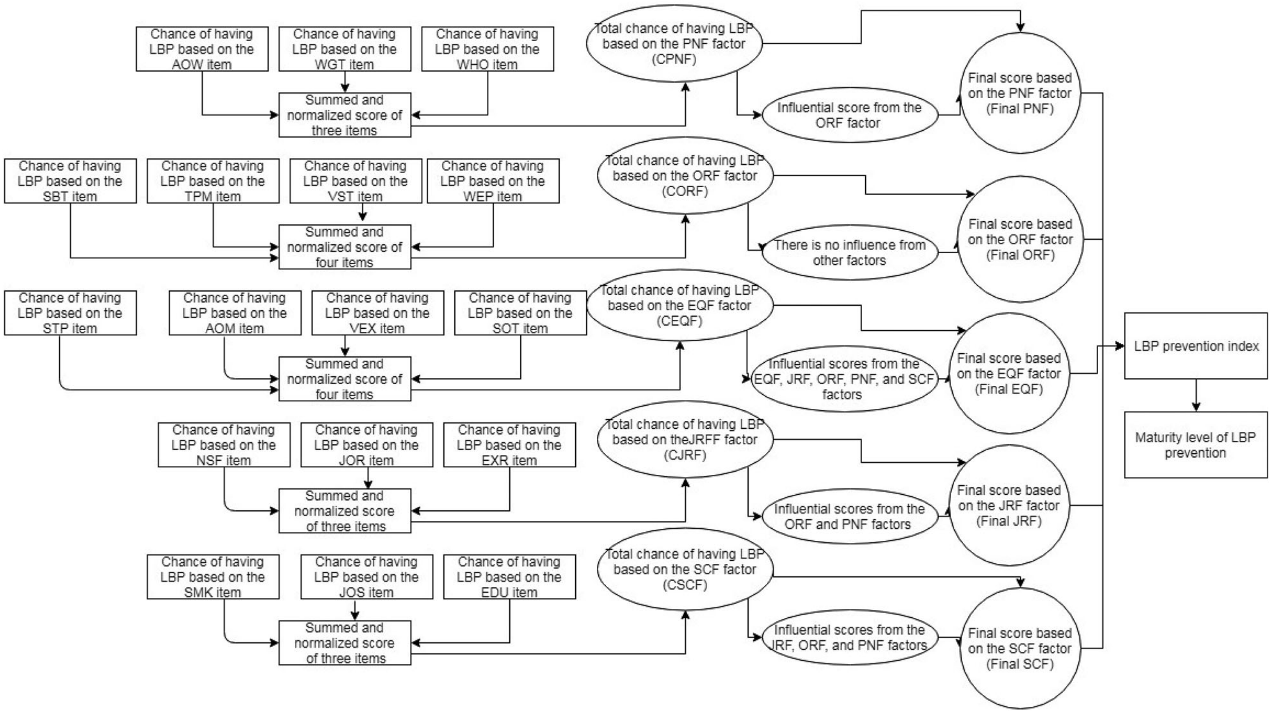

Figure 6. Flow of LBP prevention index and LBP prevention maturity level.

The final chance of having LBP based on the personal factor sub-model is then calculated by summing the total chances of having LBP with the influential score received from the ORF factor. The difference between 1000 and this final chance is, then the final score of LBP prevention for PNF factor (final PNF).

Once the final scores of the five sub-models are achieved, they are summed and normalized to a maximum of 1000 points for the LBP prevention index, to assess the current level of LBP prevention maturity.

The details of each sub-model and equation are explained next.

Personal factor sub-model

The PNF factor sub-model consists of three associated items, including (1) age of the worker (AOW), (2) weight of the worker (WGT) and (3) working hours (WHO).

Age of the worker

The chance of having LBP changes with a worker's age. According to Lant and Partners (2015), workers are separated into three age groups: group A (25–44 years old), group B (45–54 years old) and group C (more than 54 years old). Groups A, B and C have 48%, 54% and 50% chances of having LBP, respectively (Lant and Partners 2015). The chance of having LBP based on the three age-groups is calculated as in Equation (1)

$$\begin{aligned} \text{CAOW} = {} & ((48 \times \text{A\_pop\_ratio}) + (54 \times \text{B\_pop\_ratio}) \\ & +(50 \times \text{C\_pop\_ratio})) \times 1000 \end{aligned} \tag{1}$$

Weight of the worker

According to Alghadir and Anwer (2015), workers are separated into four weight ranges with different chances of having LBP. Underweight workers (PUWGT) have a 100% chance of having LBP, while normal (PNWGT), overweight (POWGT) and obese (PBWGT) workers have 40.63%, 50%, and 58.62% chances of having LBP, respectively (see Equation (2))

$$\begin{aligned} \text{CWGT} = {} & (((40.63 \times \text{PNWGT}) + (58.62 \times \text{PBWGT}) \\ & + (50 \times \text{POWGT}) + (100 \times \text{PUWGT}))) \\ & \times 1000 \end{aligned} \tag{2}$$

Working hours

In South Asian countries, including Sri Lanka, each worker works 12 hours per day (Vaid 1999). Nevertheless, Trejo (1993) recommended a maximum of eight working hours per day. Alghadir and Anwer (2015) added that workers who work eight hours per day have a smaller chance of having LBP than those who work longer hours. In this study, the health and safety budget is spent to hire additional workers and reduce working hours in each age group (see Equation (3))

$$BHO = ((AHAOs \times WHRA) + (AHBOs \times WHRB) + (AHCOs \times WHRC)) \times WW \text{ Per Year} \quad (3)$$

The total chance of having LBP due to WBV exposure based on the PNF factor (CPNF) is the average chance of the three associated items with a maximum score of 1000 points. The implementation of the PNF factor influences the implementation of the other factors, including the EQF, JRF and SCR factors. The value of CPNF affects the chances of having LBP based on the EQF, JRF and SCF factors by 100%, 47% and 55%, respectively, following the correlation coefficient values shown in Figure 2.

Organizational factor sub-model

The ORF factor sub-model consists of four items, namely the health and safety budget (SBT), training program (TPM), WBV standard (VST) and working experience (WEP).

Health and safety budget

To effectively implement the LBP prevention program, it is necessary for a company to provide an adequate health and safety budget. Pellicer et al. (2014) stated that the health and safety budget of a construction company should be approximately 5% of the total budget, with an increasing rate of 2% per year. Huang and Hinze (2006) added that the health and safety budget is commonly used in five areas, including, (1) environment and heredity, (2) personal failing, (3) unsafe behaviour or physical hazard, (4) accident and (5) injury. The LBP due to WBV exposure is categorized under the physical hazard category. The budget in this category is used to reduce the working hours and night shifts of the workers, train the workers with ergonomic-related programs, and purchase suspension seats and new machines.

Training program

According to Lahiri et al. (2005), the chance of having LBP in the three age groups, that is, A, B and C, can be reduced to 33%, 39% and 35%, respectively with proper training. In this study, the health and safety budget is used to train the HEOs based on the necessities of each age group. As group C workers are less fit than those in groups A and B, they have the priority to receive the training, to prevent LBP in the long-term. The number of trained workers in group C (CTW) depends on the budget (CSBT) allocated, and the training cost per person (CTCPP) (see Equation (4))

$$CTW = IF(Train\_year = 1)THEN(IF(ROUND(CP) > ROUND((CSBT/CTCPP))0.5)\ THEN \times (ROUND(CSBT/CTCPP) - 0.5) \times ELSE(ROUND(CP)))ELSE(0) \quad (4)$$

WBV standard

The ISO 2631 Guidelines and the EU Directives are two major international standards that consider about the WBV exposure, especially in the organizational, human and equipment perspectives by reducing the night-shift work (NSF), increasing the job rotation (JOR), reducing the working hours (WHO) and acquiring proper training (TPM) and supportive equipment (Paschold 2008).

Working experience

Janwantanakul et al. (2011) stated that workers with more than 10 years of working experience have a 10% less chance of having LBP. The total chance of having LBP due to WBV exposure based on the ORF factor (CORF) is the average chance of its associated items with a maximum score of 1000 points. The CORF affects the LBP prevention index and also influences the implementation of the other two factors, including the PNF and EQF factors.

Equipment factor sub-model

The EQF factor sub-model consists of four items, namely the seat type (STP), age of the machine (AOM), WBV exposure (VEX) and soil type (SOT).

Seat type

A common seat used with heavy equipment is a cushioned seat. However, this seat type has a 63% chance of generating LBP, while a suspension seat has 30.4% chance of generating LBP (Subhash and Ario 2011). In this study, the leftover budget after hiring and training workers is used for the purchasing of suspension seats (see Equation (5)). The chance of having LBP from the seat type (CSTP) is then based on the numbers of cushioned and suspension seats (see Equation (6))

$$\mathrm{BRSS} = \mathrm{IF(LAT>RBSS)THEN\ RBSS\ ELSE\ ROUND} \times ((\mathrm{LAT/PSS}) - 0.5) \times \mathrm{PSS} \tag{5}$$

$$\mathrm{CSTP} = ((\mathrm{CSSTP} \times \mathrm{RSS}) + (\mathrm{CCSTP} \times (1 - \mathrm{RSS})) \times 1000 \tag{6}$$

Age of the machine

The WBV emission level is high for obsolete machines. Based on Vitharana and Chinda (2016), heavy equipment should be replaced every 10 years. The leftover budget after hiring and training workers and the purchasing of suspension seats is used to purchase new machines (see Equation (7)). The chance of having LBP from the age of the machine (CAOM) is then based on the numbers of old and new machines (see Equation (8))

$$\mathrm{BRHE} = \mathrm{IF(BY = 0)\ THEN\ (ROUND((RBHE/PHE)} - 0.5))\mathrm{ELSE}(0) \tag{7}$$

$$\mathrm{CAOM} = ((\mathrm{NAOM} \times \mathrm{RNHE}) + (\mathrm{OAOM} \times (1 - \mathrm{RNHE})) \times 1000 \tag{8}$$

WBV exposure

In this study, the WBV exposure (VEX) indirectly affects the chance of having LBP from the AOM, JOR, NSF, STP, TPM and WHO items (Vitharana and Chinda 2017). The use of old machines, for example, causes a high chance of having LBP (Chaudhary et al. 2015).

Soil type

Construction work in Sri Lanka deals with different soil types, such as heavy clay, silty clay, mixture of gravel, and sand and clay. The compaction level of each soil type is different, resulting in different vibration levels for exposed workers (Government Ministry of Railways, India 2005). In this study, a maximum chance of having LBP based on the soil type (CSOT) is 63% (Kittusamy and Buchholz 2004).

The total chance of having LBP due to WBV exposure based on the EQF factor (CEQF) is the average chance of its four associated items, with a maximum score of 1000 points. The EQF factor has no influence on the other factors. Instead, this factor is influenced by the other four factors. This is reflected by the influential scores this factor receives from the other four factors (see Figure 6).

Job-related factor sub-model

The JRF factor sub-model consists of three associated items, namely, the night shift (NSF), job rotation (JOR) and exercise (EXR).

Night shift

According to Takahashi et al. (2015), workers who work the night shift experience a 42% chance of having LBP, while those who do not work the night shift have about half the chance of having LBP.

Job rotation

Frazer et al. (2003) stated that the chance of having LBP can be reduced by half by rotating jobs. In this study, the chance of having LBP based on job rotation (CJOR) is calculated from the ratio of workers with job rotation to those without job rotation (sees Equation (9))

$$\mathrm{CJOR} = ((\mathrm{CNJOR} \times (1 - \mathrm{RSTDO})) + (\mathrm{CEJOR} \times \mathrm{RSTDO})) \times 1000 \tag{9}$$

Exercise

Exercise is mentioned as a treatment for LBP (Koes et al. 2006). Workers who regularly exercise experience a 50% chance of having LBP, while those who do not exercise have an 82% chance of having LBP (Rainville et al. 2004). In this study, workers are separated into three groups: those who regularly exercise (RPEXR), sometimes exercise (SPEXR) and never exercise (NPEXR) (see Equation (10))

$$\mathrm{CEXR} = ((50 \times \mathrm{RPEXR}) + (70 \times \mathrm{SPEXR}) + (82 \times \mathrm{NPEXR})) \times 1000 \tag{10}$$

The total chance of having LBP due to WBV exposure based on the JRF factor (CJRF) is the average chance of its three associated items with a maximum score of 1000 points. The JRF factor also influences the implementation of the EQF and SCF factors by 13% and 25%, respectively (see Figure 2). This is represented by the influential scores of the EQF and SCF factors.

Social-context factor sub-model

The SCF factor sub-model consists of three associated items: job satisfaction (JOS), smoking (SMK) and education (EDU).

Job satisfaction

Hoogendoorn et al. (2002) divided job satisfaction into three different levels of having LBP: moderate with a 34.30% chance, reasonable with a 25.30% chance and good with a 19.48% chance. In this study, job satisfaction can be enhanced by hiring more workers to reduce long working hours, training workers with LBP-related programs, and providing workers with new equipment.

Smoking

According to Alghadir and Anwer (2015), the chance of having LBP among smokers is 57%, while non-smokers have a 43% chance of having LBP. The chance of having LBP based on smoking (CSMK) is as shown in Equation (11)

$$\mathrm{CSMK} = ((1-\mathrm{PSMK}) \times 43) + (\mathrm{PSMK} \times 57))\times 1000 \tag{11}$$

Education

Workers with different educational backgrounds have different chances of experiencing LBP. According to Udom et al. (2016), workers with the bachelor's degree, high school and primary school background have, 41.5%, 45.8% and 64.6% chances of having LBP, respectively.

The total chance of having LBP due to WBV exposure based on the SCF factor (CSCF) is the average chance of its three associated items with a maximum score of 1000 points.

LBP prevention index sub-model

The final chance of having LBP due to WBV exposure comes from the implementation of each factor, and also the influential scores of the five key factors. For example, the final chance of having LBP due to WBV exposure of the EQF factor is achieved from its total chance of having LBP and the influential score this factor achieved from the implementation of the PNF, ORF, JRF and SCF factors (see Equation (12)). It is converted to a final score of LBP prevention, as shown in Equation (13)

$$\begin{aligned}\mathrm{Final\ chance\ EQF} = (\mathrm{CEQF} + ((\mathrm{delta\_CPNF} \times 1)\\ -(\mathrm{delta\_CSCF} \times 0.2)\\ -(\mathrm{delta\_CJRF} \times 0.13))\\ -(\mathrm{delta\_CORF} \times 0.20)\end{aligned} \tag{12}$$

$$\mathrm{Final\ EQF} = 1000 - \mathrm{Final\ chance\ EQF} \tag{13}$$

The LBP prevention index (PILBP) is then achieved by summing and normalizing the final scores of the five key factors (see Equation (14)). This index score is used to assess the current level of LBP prevention maturity (see Equation (15))

$$\begin{aligned}\mathrm{PILBP} = (\mathrm{Final\ ORF} + \mathrm{Final\ PNF} + \mathrm{Final\ SCF}\\ + \mathrm{Final\ JRF} + \mathrm{Final\ EQF})/5\end{aligned} \tag{14}$$

$$\begin{aligned}\mathrm{Maturity\ index} = \mathrm{IF(PILBP{<}200)\ THEN\ 1\ ELSE}\\ \times \mathrm{(IF(PILBP = 200OR(PILBP{>}200}\\ \times \mathrm{AND\ PILBP{<}400))\ THEN\ 2}\\ \times \mathrm{ELSE\ (IF(PILBP = 400OR(PILBP}\\ \mathrm{{>}400\ AND\ PILBP{<}600))\ THEN\ 3}\\ \times \mathrm{ELSE\ IF(PILBP = 600OR(PILBP}\\ \mathrm{{>}600\ AND\ PILBP{<}800))\ THEN\ 4}\\ \times \mathrm{ELSE\ IF(PILBP = 800OR(PILBP}\\ \mathrm{{>}600\ AND\ (PILBP{<}1000\ OR\ PILBP}\\ \mathrm{= 1000)))THEN5ELSE0))}\end{aligned} \tag{15}$$

Simulation results

The dynamics model of the LBP prevention index is simulated and the results are shown in Figure 7 and Table 4. In the beginning years, a construction company achieves level 2 for LBP prevention maturity with an LBP prevention index of about 269 points. This is because the company has some young-age workers with different working experiences and educational backgrounds.

It takes three years for the company to progress from level 2 to level 3 of maturity when the health and safety budget is provided to improve the LBP prevention index. At this level, the company follows the ISO 2631 Guidelines and EU Directives by focusing on reducing working hours, cutting-off night shifts and improving job rotation. A specific training program is also initiated to enhance the LBP-related knowledge.

The company spends four more years to progress from level 3 to level 4 of maturity. At this level, workers have full awareness of LBP symptoms and attempt to avoid them. The company provides a large budget to train workers with LBP-related programs and purchases new equipment to reduce the chances of having LBP.

After level 4 is achieved, it takes 30 years for the company to achieve the highest level of maturity. The company must focus on continuous improvement with adequate provisions of the health and safety

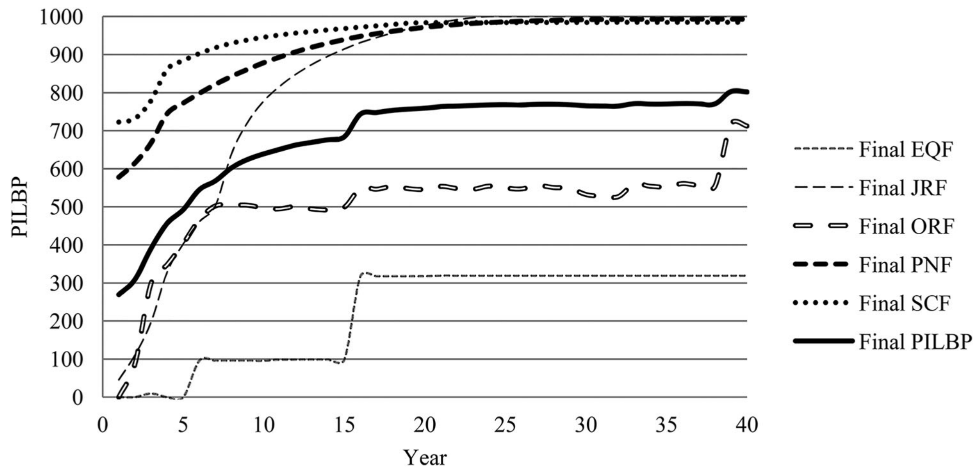

Figure 7. Simulation results of the dynamics model of the LBP prevention index.

Table 4. Simulation results of LBP prevention index and LBP prevention maturity level.

	LBP prevention index (points)						
Year	Final EQF	Final JRF	Final ORF	Final PNF	Final SCF	PILBP	Maturity level
1	0.00	45.66	0	578.06	722.75	269.29	2
2	0.00	110.85	86.99	615.22	731.92	309.00	2
3	9.45	197.37	298.62	667.74	779.11	390.46	2
4	0.00	328.49	348.18	744.63	860.97	456.46	3
5	0.00	402.55	403.18	772.57	884.34	492.53	3
6	95.92	460.79	466.61	798.17	902.75	544.85	3
7	95.92	503.56	502.67	821.87	917.97	568.40	3
8	95.92	639.90	503.79	842.88	929.84	602.47	4
9	95.92	722.43	504.42	861.44	938.32	624.50	4
10	95.92	778.11	496.56	878.85	945.61	639.01	4
11	98.67	817.16	494.90	893.65	951.42	651.16	4
12	98.67	848.59	501.51	907.46	956.52	662.55	4
13	98.67	874.35	494.45	919.67	960.55	669.54	4
14	98.67	896.01	492.03	930.12	964.79	676.33	4
15	98.67	914.59	499.08	939.62	968.29	684.05	4
16	317.58	931.52	548.23	948.08	972.14	743.75	4
17	317.58	944.67	546.45	955.02	975.38	747.82	4
18	317.58	956.87	553.93	961.36	979.02	753.75	4
19	317.58	967.51	547.82	966.81	982.60	756.46	4
20	317.58	976.69	546.02	971.77	983.79	759.17	4
21	319.20	984.62	553.86	975.77	983.97	763.48	4
22	319.20	991.41	548.25	979.23	984.10	764.44	4
23	319.20	997.14	546.40	982.19	984.21	765.83	4
24	319.20	1000.00	554.61	984.12	984.32	768.45	4
25	319.20	1000.00	549.18	986.10	984.09	767.71	4
26	319.20	1000.00	547.31	987.63	984.16	767.66	4
27	319.20	1000.00	555.95	989.07	984.23	769.69	4
28	319.20	1000.00	550.76	990.13	984.29	768.88	4
29	319.20	1000.00	548.96	990.99	984.33	768.70	4
30	319.20	1000.00	532.43	991.81	984.37	765.56	4
31	319.17	1000.00	527.85	992.34	984.39	764.75	4
32	319.17	1000.00	526.91	992.56	984.64	764.66	4
33	319.17	1000.00	559.55	992.98	984.63	771.27	4
34	319.17	1000.00	554.16	993.02	984.61	770.19	4
35	319.17	1000.00	552.32	993.12	984.58	769.84	4
36	319.17	1000.00	561.32	993.21	984.77	771.69	4
37	319.17	1000.00	555.83	993.23	984.71	770.59	4
38	319.17	1000.00	554.03	993.28	984.87	770.27	4
39	319.17	1000.00	717.67	993.14	984.80	802.96	5
40	319.17	1000.00	712.47	992.95	984.91	801.90	5

budget to conform to standard working hours, cut-off night shifts and support all LBP-related activities.

Table 4 shows that the JRF factor achieves a maximum final score for LBP prevention of 1000 points at the end of year 24, which is the earliest among the five key factors. This is based on the provisions of the budget to reduce night-shift work and improve job rotation. The EQF factor, however achieves a final

Table 5. Simulation results of LBP prevention index with different SBT increasing rates.

	LBP prevention index (points)				
Year	SBT 2%	SBT 4%	SBT 6%	SBT 8%	SBT 10%
1	269.29	269.29	269.29	269.29	269.29
2	309.00	309.00	309.00	309.00	309.00
3	390.46	390.46	390.46	390.46	390.46
4	456.46	456.46	456.46	456.46	456.46
5	492.53	492.53	492.53	492.53	492.53
6	544.85	555.40	561.00	566.00	571.34
7	568.40	577.49	582.86	587.86	593.19
8	602.47	614.64	620.51	625.51	630.84
9	624.50	640.96	654.73	661.50	666.83
10	639.01	654.36	668.26	675.10	680.43
11	651.16	666.02	679.14	686.25	691.94
12	662.55	676.85	692.57	700.90	706.59
13	669.54	683.27	698.37	706.55	712.25
14	676.33	689.04	703.47	711.53	717.23
15	684.05	696.29	713.57	720.50	726.19
16	743.51	749.86	761.98	763.75	764.07
17	747.82	753.29	764.93	766.65	766.97
18	753.75	758.54	773.08	773.62	773.94
19	756.46	760.34	774.31	774.85	775.17
20	75917	762.62	776.08	776.60	776.92
21	763.48	766.62	782.98	784.19	785.91
22	764.44	767.39	783.19	784.39	786.11
23	765.83	768.61	783.88	785.09	786.80
24	768.45	771.20	787.97	789.17	790.89
25	767.71	770.93	787.29	788.50	790.21
26	767.66	770.73	787.56	787.77	789.49
27	769.69	771.84	789.62	790.83	792.55
28	768.88	770.93	788.15	789.35	791.07
29	768.70	770.66	787.32	788.53	790.25
30	765.56	771.44	790.23	791.43	793.15
31	764.75	771.95	791.16	795.15	800.20
32	764.66	771.59	790.22	794.21	799.27
33	771.27	772.23	792.99	796.97	802.03
34	770.19	771.16	791.29	795.27	800.33
35	769.84	770.81	790.33	794.32	799.37
36	771.69	772.61	793.03	797.02	802.08
37	770.59	771.52	791.31	795.30	800.35
38	770.27	771.17	790.35	794.34	799.40
39	802.96	806.31	826.38	830.36	835.42
40	801.90	801.15	824.59	828.58	833.63

score for LBP prevention of only 319.17 points at the end of year 40. This may be because there is not enough in the budget to replace old machines, as each machine costs over 100,000 USD.

To further improve the LBP prevention index, different health and safety budget increasing rates are tested with the developed model, from a minimum of 2% to a maximum of 10% (Jaselskis et al. 1996). Table 5 and Figure 8 show that the LBP prevention index is improved when more health and safety budget is provided. With a 10% increasing rate of the health and safety budget, the LBP prevention index reaches level 5 of maturity in 30 years.

A closer examination of budget spending to improve the LBP prevention index reveals two areas of improvement: human resource and equipment acquisition. The results in Figure 9 show the importance of human resource over equipment acquisition with a higher prevention index in the long-term.

Conclusion

LBP due to WBV exposure is a health hazard among HEOs in the construction industry. This study develops a dynamics model of the LBP prevention index based on five key factors and their 17 associated items to examine and improve the LBP prevention program in the long-term. Five levels of LBP prevention maturity are used, together with the LBP prevention index achieved from the developed model, to assess the current level of LBP prevention maturity, and plan for long-term improvement.

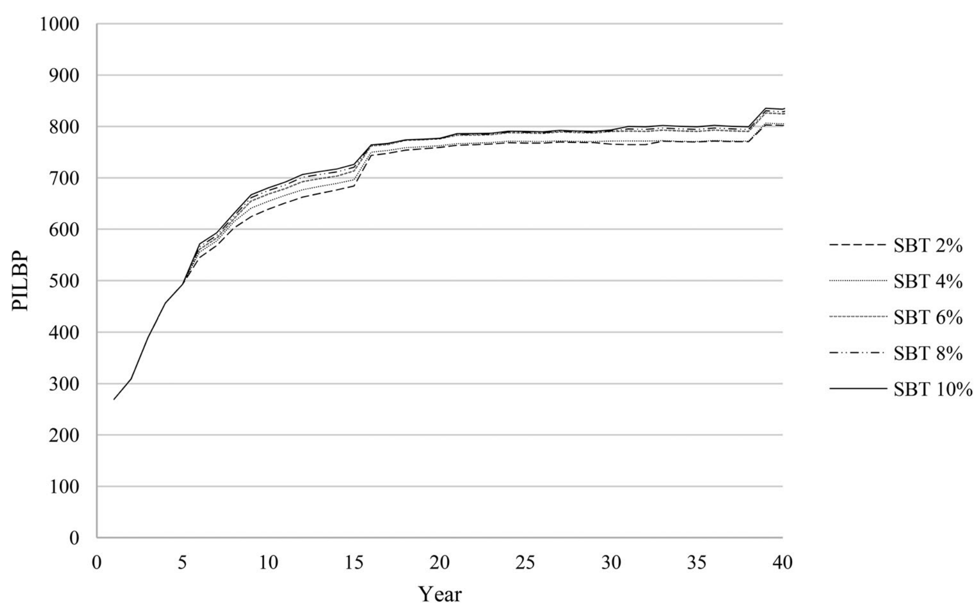

Figure 8. LBP prevention index with different SBT increasing rates.

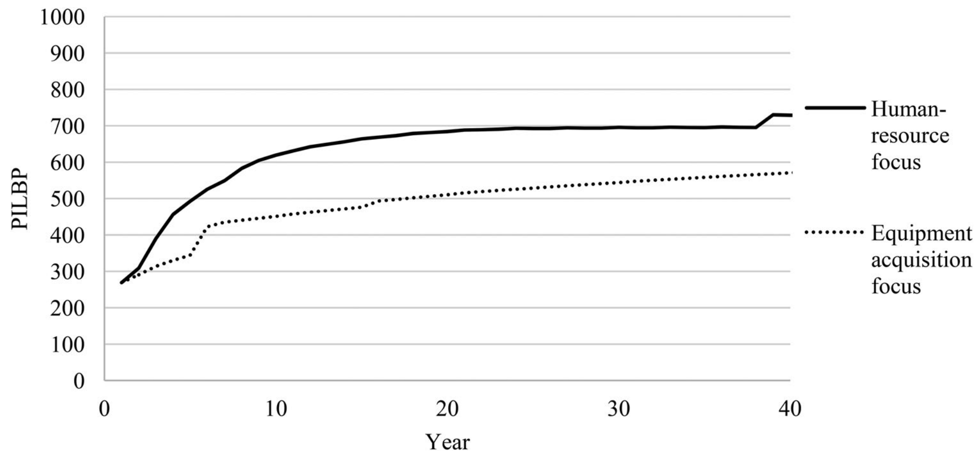

Figure 9. PILBP with human resources and equipment acquisition.

The simulation results show that a construction company is currently at level 2 of LBP prevention maturity. With support from management, the company reaches levels 3 and 4 of maturity in four and eight years, respectively. To achieve the top maturity level, however, this takes both effort and support, mainly on budgeting, to proceed with program implementation. With continuous improvement, the company reaches the top maturity level at the end of year 39.

The results show the importance of human resources over equipment acquisition to achieve higher maturity levels. The company should, therefore, focus more on providing an adequate budget to support with LBP-related activities, such as LBP-related training and job rotation, to reduce the chances of having LBP.

The construction industry can use the dynamics model of the LBP prevention index to better understand LBP prevalence. The developed model can also assist management in effectively utilizing the health and safety budget to reduce the chance of having LBP, and plan for progress through higher levels of LBP prevention maturity in the long-term.

This research study has some limitations. The study does not directly include some qualitative items, such as gender, weather, work pressure and work posture. Moreover, the initial data used in model development are based on the Sri Lankan construction industry. Some adjustments may be needed when applied to other countries.

Disclosure statement

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Appendix

Full names of abbreviation
A_pop_ratio = Ratio of group A population to total population
AHAOs = Additional hired HEOs in A group
AHBOs = Additional hired HEOs in B group
AHCOs = Additional hired HEOs in C group
B_pop_ratio = Ratio of group B of population to total population
BHO = Budget spending for worker hiring
BRHE = Buying rate of heavy equipment
BRSS = Buying rate of suspension seat
BY = Heavy equipment replacing year
C_pop_ratio = Ratio of group C population to total population
CAOM = Chance of having LBP based on the age of HEOs
CAOM = Chance of having LBP due to WBV exposure based on age of the machine
CCSTP = Chance of having LBP due to WBV exposure based on suspension seat
CEJOR = Chance of having LBP due to WBV exposure with job rotation
CEQF = Chance of having LBP due to WBV exposure based on the EQF factor
CEXR = Chance of having LBP due to WBV exposure based on exercise
CJOR = Chance of having LBP due to WBV exposure based on job rotation
CJOS = Chance of having LBP due to WBV exposure based on job satisfaction
CJRF = Chance of having LBP due to WBV exposure based on the JRF factor
CNJOR = Chance of having LBP due to WBV exposure without job rotation
CORF = Chance of having LBP due to WBV exposure based on the ORF factor
CP = Portion of the group C HEOs entitled to receive training
CPNF = Chance of having LBP due to WBV exposure based on the PNF factor
CSBT = Allocated budget group C training
CSCF = Chance of having LBP due to WBV exposure based on the SCF factor
CSMK = Chance of having LBP due to WBV exposure based on smoking
CSOT = Chance of having LBP due to WBV exposure based on soil type
CSSTP = Chance of having LBP due to WBV exposure based on cushioned seat
CSTP = Chance of having LBP due to WBV exposure based on seat type
CTCPP = Training cost per HEOs in group C
CTW = Number of trained workers in group C
CWGT = Chance of having LBP based on weight
CWHO = Chance of having LBP based on working hours

delta_CJRF = Change of chances of having LBP due to WBV exposure of the JRF factor
delta_CORF = Change of chances of having LBP due to WBV exposure of the ORF factor
delta_CPNF = Change of chances of having LBP due to WBV exposure of the PNF factor
delta_CSCF = Change of chance of having LBP due to WBV exposure of the SCF factor
Final chance EQF = Final chance of having LBP due to WBV exposure based on the EQF factor
Final chance JRF = Final chance of having LBP due to WBV exposure based on the JRF factor
Final chance ORF = Final chance of having LBP due to WBV exposure based on the ORF factor
Final chance PNF = Final chance of having LBP due to WBV exposure based on the PNF factor
Final chance SCF = Final chance of having LBP due to WBV exposure based on the SCF factor
Final EQF = Final score of LBP prevention based on the EQF factor
Final JRF = Final score of LBP prevention based on the JRF factor
Final ORF = Final score of LBP prevention based on the ORF factor
Final PNF = Final score of LBP prevention based on the PNF factor
Final SCF = Final score of LBP prevention based on the SCF factor
LAT = Leftover budget after training
NAOM = Chance of having LBP due to WBV exposure with new heavy equipment
NPEXR = Portion of HEOs with no exercise
OAOM = Chance of having LBP due to WBV exposure with old heavy equipment
PBWGT = Percentage of obese HEOs
PHE = Price of heavy equipment
PILBP = LBP prevention index
PNWGT = Percentage of HEOs with normal weight
POWGT = Percentage of overweight HEOs
PSMK = Prevalence of smoking habit among workers
PSS = Price of a suspension seat
PUWGT = Percentage of underweight HEOs
RBHE = Leftover budget for heavy equipment purchasing
RBSS = Required budget for suspension seat purchasing
RNHE = Ratio of new heavy equipment to total heavy equipment
RPEXR = Portion of HEOs who exercise regularly
RSS = Ratio of suspension seats to total seats
RSTDO = Ratio of standard operators to total operators
SPEXR = Portion of HEOs who exercise sometimes
Train year = Year of training
WHRA = Weekly hiring rate of group A HEOs
WHRB = Weekly hiring rate of group B HEOs
WHRC = Weekly hiring rate of group C HEOs
WWPerYear = Number of weeks per year