Ergonomic Assessment of Residential Construction Tasks Using System Dynamics

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Abstract-Modular residential construction activities often require prolonged standing, bending, stooping, and material handling, while working in crowded spaces; these activities increase the potential risk of work-related musculoskeletal disorders (WRMSDs), which may worsen over time, resulting in permanent disability and, consequently, the loss of ability to work. The use of system dynamics (SD) modeling to assess ergonomic risks provides a decision support tool for job managers and job designers and delivers a powerful graphical illustration, showing the logical links between cause and effects and helps illustrate how ergonomic risks may lead to WRMSDs. This paper presents a SD model for ergonomic analysis of residential construction tasks. A case study is presented and used to evaluate variations in risk exposure to identify most contributing factors to potential ergonomic injury. Also a literature review is performed to identify the main ergonomic risk variables. The results are expected to assist project participants in controlling and assessing ergonomic risks leading to improved work efficiency, safety and reduced lost time injuries and related cost, insurance premium (WCB) and claims caused by WRMSDs.

Keywords: residential construction task; system dynamics; ergonomic risk

1 Introduction

Construction productivity correlates to how well, how quickly and at what cost buildings and infrastructure can be constructed and can influence prices of homes, consumer goods and the strength of the national economy [13]. While only 63% of traditional building projects are completed on time [15], the off-site fabrication method has made significant advances in the last two decades, offering benefits in several major areas including productivity improvement [8] by shifting house construction to a manufacturing process [7]. Although the manufacturing process brings many benefits to construction projects; it is also challenged with different internal and external risk factors [9]. By moving the construction process from on-site to factory, most of the tasks are performed in manufacturing facilities and include physically demanding tasks, that expose construction workers to a number of ergonomic risks leading to (WRMSDs).

WRMSDs have been a major cause of non-fatal injuries in construction in the United States accounting for almost 33% of all occupational injuries [4]. In Canada the total cost of occupational injuries to the economy, considering direct and indirect costs, is more than $19 billion annually [10]. WRMSDs develop over time as a result of exposure to factors such as, awkward posture, contact stress, hand/arm vibration, force/static load, and repetition. Also the work pace (organizational factors) and environmental factors contribute to the risk of WRMSDs. Symptoms of WRMSDs may include pain, aching, discomfort, numbness, tingling, and swelling, and normally occur in the back, shoulders, neck, legs, wrists, fingers, elbows, and arms [4]. WMSDs are attributable to a combination of interacting risk factors [2]. The main concept underlying the application of ergonomics to reduce musculoskeletal injury is to match the job to the worker capacity based on the characteristics of the worker, rather than requiring the worker to adapt to the job [5]. Thus proactive ergonomic practices and periodical ergonomic risk assessments can help to identify and eliminate exposure to risk factors and ensure safer construction work conditions, reduces occurrence of WRMSDs and consequently improves quality and productivity of the process. A number of different methods have been developed to evaluate the existence of ergonomic risks. Rapid Upper Limb Assessment (RULA) is a survey method consisting of a single page worksheet which generates only a single risk score associated with upper limbs [3]. Rapid Entire Body Assessment (REBA), just like RULA, is a single worksheet but it evaluates body posture, forceful exertions, type of movement, repetition, and rapid changing associated with the task [12]. Quick

Exposure Check (QEC) assesses work risks related to the back, wrist, neck, and shoulder/arm and is based on epidemiological evidence of the observer's ability to differentiate between different levels of exposure [6]. The Ergonomic Workload Stress Index (EWSI) model is based on the concept of fuzzy set theory to predict the existence and level of ergonomic workload stress; however this model is challenged with the problem of fitting fuzzy logic to human judgment data and accommodating the issue of vagueness of human language [11]. Other methods include the Ovako Working Posture Analysis System (OWAS) which is mainly developed for use in medium to heavy assembly tasks in steel industry to identify and evaluate poor working postures [14]. The Three-dimensional Static Strength Prediction Program (3DSSPP), which is based on biomechanical analysis concepts, considers the worker's posture, gender, anthropometry factors (weight and height), and forces on the hand. It calculates spinal compression and shear forces at L5/S1 disc [16]. However none of the aforementioned methods integrates hand arm vibration exposure, effect of organizational and environmental factors. ErgoCheck is an ergonomic assessment framework which quantifies risks associated with modular and panelized residential construction tasks considering awkward posture, contact stress, force and static loading, repetitive tasks, hand arm vibration and environmental factors as well as the organizational factors [22].This method is selected as the basis of this study for the purpose of developing an integrated ergonomic tool using system dynamics (SD) as it offers a body part based analysis and rating of ergonomic risk.

System thinking, which is a compelling solution for many real world problems, refers to the paradigm in which the world is seen as a complex system, in which everything is connected to everything else [17]. SD, as a powerful graphical illustration tool, is capable of showing the logical links between cause and effects, and has been implemented where a holistic view is essential and feedback loops are critical in understanding the interdependencies among the variables included in the system. SD models are capable of addressing a variety of the problems identified in the literature, ranging from environmental or public policy, to corporate strategy, security, healthcare, and operations management.[19].However there has been no extensive application of SD reported in the ergonomic analysis literature. SD modeling is suitable for any dynamic system characterized by mutual interactions, information feedback, and interdependencies among variables. The behavior of complex systems and consequences of different policies involved in the system can be examined throughout the process by means of a philosophy that reviews problems from a globally perspective [20]. **T**he application of SD allows a four stage approach: (1) recognizing the problem. To have a successful model the modeler must have a clear understanding of the problem. A full understating of the models is often beyond the capacity of human cognition therefore, it should be broken down into smaller systems without violating the holistic concept of SD; (2) Describing the system by means of causal loop diagrams also known as influence diagram; (3) qualitative analysis that involves analyzing the causal loops closely; (4) construction of simulation model. This step covers specification of the structure and decision rules. The estimation of variables, behavioral relationships, and initial conditions should be quantified at this stage [21]. While all the existing SD computer packages use the same modeling concept, the three most widely used packages are STELLA/iThink, Powersim, and Vensim (which is the package used in this research). Different types of components as well as the modeling process are explained more fully in the methodology section below.

The objective of this research is to develop an SD model application for ergonomic analysis of residential construction tasks. The proposed methodology focuses on; (i) identifying principal components of the system, (ii) providing comprehensive ergonomic risk factors based on the existing literature, (iii) developing causal loop diagrams to illustrate the relationships among the variables in the system, and (iv) exploring different what-if scenarios and policy tests as a result of changes in variables which eventually will lead to increase confidence in particular job design strategies, task cycle strategies and policies. The proposed methodology is represented in figure 1.

2 Methodology

The application of SD is a four stage approach in which the first step is recognizing the problem. The model designer must develop a reference model composed of descriptive data illustrating the behavior of the problem. The reference model assists the modeler in obtaining holistic view of the problem. As the primary goal of this study is to build an SD model application for ergonomic analysis of residential construction tasks, the hazard quantification rating system developed by Inyang et al [22] is selected as the basis reference model in the process of ergonomic risk assessment in this research. This is because other existing ergonomic assessment methods mainly focus on awkward posture, repetition, force and static loading, while the selected reference model considers all of the aforementioned factors as well as hand/arm vibration, contact stress, and organizational and environmental factors. After selecting the reference model, it is important to choose a proper time horizon for the SD model, and to define variables and impressions that the modeler deems significant for understanding and discussing the problem[17].

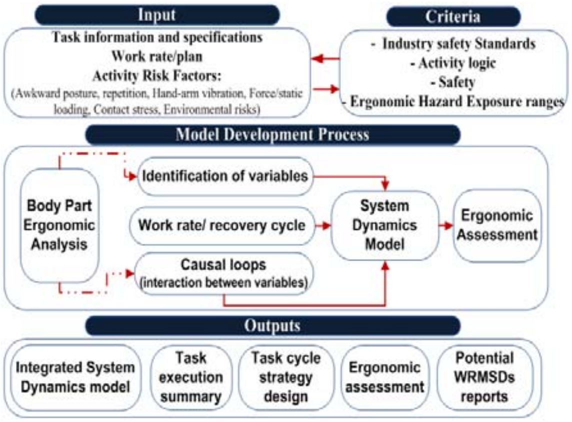

Figure 1. Methodology of Integrated System Dynamics Model Development

2.1 List of variables

There are four types of variables in SD: (1) level (those representing accumulation in the system); (2) flow (those the value of which changes over time); (3) constant (variables the value of which doesn't change over time); and (4) auxiliary (any variables computed from other variables at a given time). The causal loop diagram is a good starting point for developing an SD model; however, the list of variables and their type should first be identified. A hazard is anything that can cause harm or adverse effects and may be biological, physical, ergonomic, chemical, or psychosocial. Having identified the variables, they are categorized into three main groups: (i) hazard score which includes postural hazard, force/static load risk, hand/arm vibration, contact stress and environmental risks. (ii) Organizational risk factor and, (iii) impact of time (repetition and cycle time).

2.2 Relationships among the variables

Developing a solid causal loop diagram can be viewed as a foundation block for a continuous simulation model. A causal loop diagram illustrates the relationships among the variables in a system and can be useful during the early stages of model conceptualization and identifying principal components of the system [21]. In this study, factors such as postural hazard, force/static load risk, contact stress, hand/arm vibration and environmental risks are assumed to be constant during the simulation process. The developed model evaluates the existence of ergonomic risks while a specific posture is held during the performance of tasks under definite working conditions. As Figure 2 illustrates, a hazard score results from the evaluation of six ergonomic risk factors which are evaluated separately for each body part. (1) Postural hazard, considers the relative position of the body segments while performing work activities and is measured and valued in terms of the angle by which a specific joint deviates from the neutral position. (2) Forceful/ static exertion, represents the amount of muscular effort required to perform a task based on the weight of object, the location of object compared to shoulder and knee, and the distance of carrying the load, as well as the load characteristic, which shows how manageable the load is to be carried; (3) Contact stress risk, implies the repeated contact of the body with a hard surface or edge and level of pressure on the skin; (4) Hand arm vibration, pertains to vibration applied to the hand/arms through a tool or piece of equipment [22].

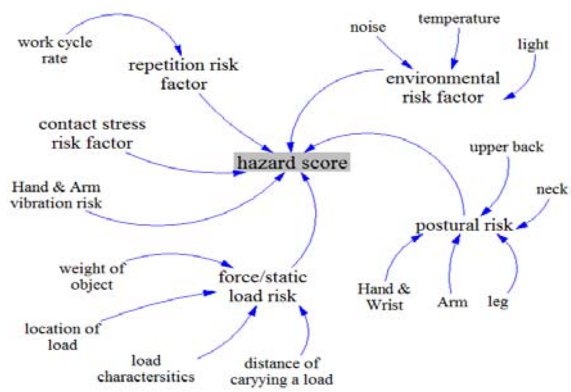

Figure2. Overview of hazard score variables

(5) Environmental factors, refers to the prevailing conditions of the work environment and their adverse effects on the worker's health including sources and levels of light that provide too much or too little illumination, cold and excessively warm temperatures and level of noise distraction; (6) Repetitive factor refers to the frequency or number of similar exertions performed during a task. Repetitive tasks are those with cycle times lasting less than 30 seconds or in which 50% of the cycle involves performing the same fundamental activities [22]. Generally, the greater the number of repetitions, the greater the degree of risk of cumulative trauma injuries; however, there is no specific repetition limit or threshold value (cycles/unit of time, movements/unit of time) associated with injury, which is why this study aims to highlight the impact of cycle time and its frequency on the development of WRMSDs.

Organizational risk factors refer to aspects of how a job is organized; these factors are based on work recovery cycle, work rate and degree of difficulty in keeping pace, workers control over work and level of mental stress [22]. Although existing statistical analysis shows a moderate correlation between mental stress and physical exhaustion, and also the development of mental stress as task duration and repetition increase, in this study these levels have been assumed to be constant through different job cycles. Further research is required to quantify the interaction between psychosocial risks and physically hazardous risks as well as development of mental stress over time [23]. Figure 3 illustrates the organizational factor as well as its associated sub-factors, which have been developed according to the organizational risk scoring system by Inyang and Al-Hussein [22]. The symbols "+" and "–"included in the diagram, represent the causal direction. While the sign '-'in the diagram represents the change in the opposite direction, the sign '+' implies a change in the same direction.

Figure 3. Organizational risk factors and related variables

It is imperative to identify a proper time horizon for the simulation process and to define those variables and impressions that seem to be significant for understanding the problem, and for planning policies to rectify it. The time horizon should meet two criteria: (1) it should begin far enough in the past to indicate how the problem occurred; and (2) it should span far enough into the future to cover the delayed and indirect effects of the potential policies [17].Since this study evaluates the ergonomic risks associated with tasks during the work day, the selected time horizon is eight hours (total daily working hours) and the time interval is one minute. Based on the ergonomic model presented by Inyang and Al-Hussein [22], the resultant hazard score of each body part during assessment (R_S) is calculated by Equation 1:

$$R_S = H_S * M_d * M_o \qquad (1)$$

where, H_S is the hazard score, M_o is the organizational risk factor, and M_d is the total daily exposure duration calculated based on the number of accomplished cycles in the day, activity cycle time and percentage of activity time during which a specific body part is exposed to risk factors. Figure 4 shows the causal links for the duration exposure factors including major variables in the developed system.

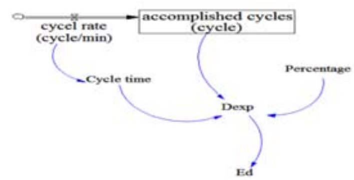

Figure 4. Graphical illustration of duration factors

2.3 Mathematical modeling process

SD simulations are developed based on a set of mathematical equations that represent interactions among variables. It should be mapped based on defined cause and effect relationships in the system using simple mathematical forms and can be either inserted into the system to represent the interactions among variables or added to the model using other methods such as tables of function. Tables of function also known as lookup tables, are typically used in SD to show nonlinear relationships between two variables. A table of function is easier to interpret and visualize and can be modeled as a list of numbers whereby input values to a function are positioned relative to the x axis and output values are read from the y axis. By employing these tables, a user can control the shapes, slopes and saturation points to represent the relationship more accurately [18].These tables are utilized in this study in order to model interactions among variables based on the ErgoCheck ergonomic risk scoring system [22]. The developed model includes separate normalized inputs for major variables rather than normalizing the input variable within itself as normalization helps examine variables without a need to redesign functions for each change in a given variable. For instance, the lookup table below (Figure5) shows the relationship between daily hazard exposure (M_d) and total daily exposure duration (D_{exp}). D_{exp} is calculated based on the number of cycles of activity during the day (n), activity cycle time (CT), and percentage of activity time during which a body part is exposed to a risk factor [22]:

$$D_{exp} = n * CT * P_{ex} \qquad (2)$$

After defining the structure of the SD model, continuous simulation is conducted in order to model all the variables included in the model and to evaluate the ergonomic risks associated with performance advancement over a time horizon of eight hours with time intervals of 1 minute.

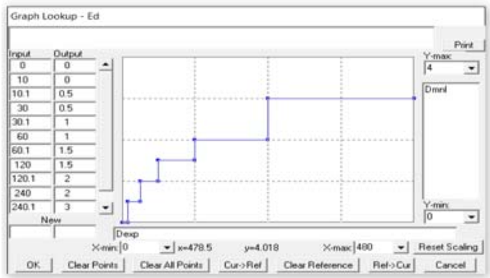

Figure 5. Table of function for daily duration risk factors

3 Case Study

Data obtained from 25 hourly observations of the sanding workstation at the Nava Cabinet Solutions production facility, a kitchen cabinet manufacturing company based in Edmonton, Canada, is used to assess the applicability of the developed simulation model. Manufacture of kitchen cabinets is a complex process that consists of many operations and requires many skills, which include shaping, tasks involving the operation of machinery such as cutting and edge banding; sanding, repetitive tasks involving excessive bodily motions; and cabinet assembly. The sanding operation consists of smoothing the surface of wooden sheets using a hand-operated power sander while both hands are used to carry out this task. The dominant hand is used to operate the sander while the other hand is used to hold the sheet of wood (Figure 6).

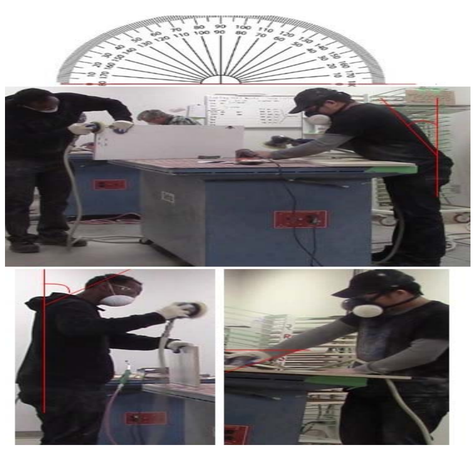

Figure 6. Body posture observation during sanding process

The developed SD model is implemented to assess the existence of ergonomic risk at the sanding station based on observed body postures, activity rate, cycle time, and related organizational risk factors.

4 Results and Validation

Having identified the body parts and range of major ergonomic risk factors involved in performing tasks through observations, the proposed SD model is applied to assess the hazard score over time cycles for each body part. Sanding operators are exposed to the risk of repetitive motion injuries and hand/arm vibration due to induced stress, and forceful movements. Significant body parts identified as “exposed” include hands, neck, and arm/shoulder. To complete a task, the sanding operator must pick up the sheet, place the sheet on the work bench, sand the sheet (which may involve either manual sanding or using a vibrating sander), and then pile the sheet for any further required operation (Figure 6). Since the sanding operation itself is a major task in the work station, it is selected as the main task for the purpose of ergonomic evaluation. The cycle time as well as the cycle rate of the sanding operation can vary depending on the size of the sheet. An average of 0.54cycles/minute and a 55% exposure rate to repetitive risk during activity are estimated based on video observations. The evaluation conditions for organizational risk factor, including mental stress, work rate difficulty, and worker’s control over work are observed. Table 1, developed based on the study by Inyang and Al-Hussein [22], shows the risk classification.

Table 1. Risk range classification

Risk Score Range	Risk Classification
$R_S < 6$	Low risk
$6 <= R_S < 13$	Medium risk
$13 <= R_S < 15$	High risk

Figure 7, illustrates the development of R_S resulting from repetition risk over 480 minutes (eight working hours). This can assist job designers and managers to design the recovery cycle in a manner which mitigates the risk related to task repetition. Figure 10 provides an overview of the developed SD model for ergonomic evaluation resulting from repetition risks.

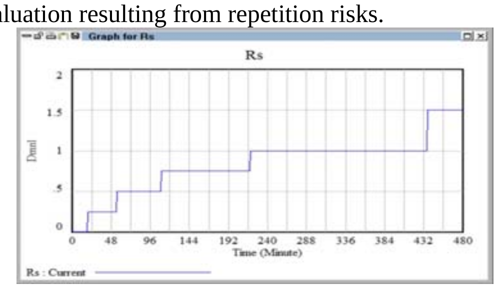

Figure 7. Development of resultant hazard score (Rs) over time

Exposure to vibration puts the hand and wrist of the operator at risk. To evaluate the impact of vibration risk, sanding operations using the vibrating sander are selected. Based on the tool vibration data, the vibration magnitude is 1.9 m/s^2, and video observations show an average of 0.56 cycle rate and 57% of exposure during activity. Figure 8 shows the resultant risk score for vibration risk factor in comparison to vibration exposure limit recommended by the American Conference of Governmental Industrial Hygienists [2]:

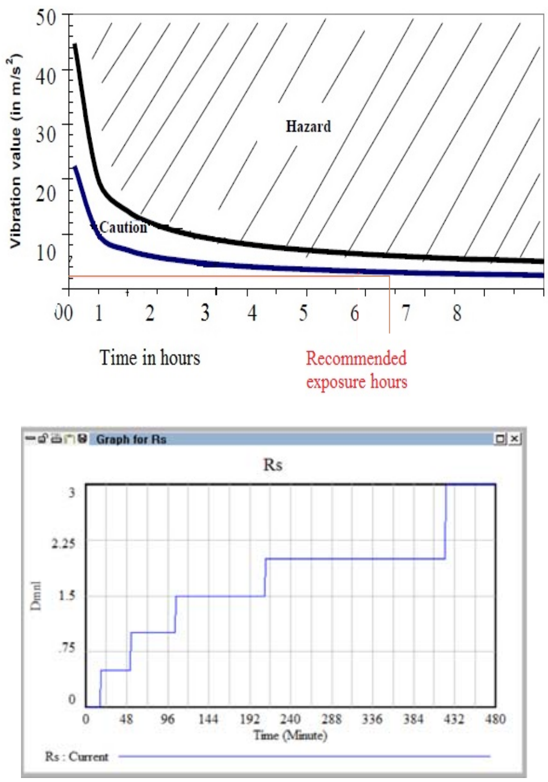

Figure 8. Comparison of resultant risk score and time hours recommendation by American conference of governmental industrial hygienists

A postural analysis is performed for major body parts involved in the task including neck, hand/wrist, and arm/shoulders. Considering the different ranges of movements observed through the operation as well as exposure duration to the posture, cycle rate and percentage of exposure, the resultant risk scores related to postural hazard for each body part are identified from the developed SD model. Table 2 summarizes the resultant risk score associated with each body part; showing the summary of daily exposure durations and risk classification for the neck, hand/wrist, and arm/shoulder. Workers are exposed for about 2.7 daily hours to 20-90° flexed neck posture, 3.16 hours hands and wrist flexion, and 4.56 hours of upper arm flexion > 45°. While methods such as REBA and RULA show risk scores of 3 and 4 respectively, representing low risk associated with the task, the proposed model clearly shows a breakdown of risk classification by body part. As illustrated in Figure 9, R_S resulting from neck posture shows a medium risk after 350 minutes while prior to that, the risk rate falls within the low risk category. Hand/wrist postural risk is classified as "medium" after 300 minutes (5 hr). Likewise, arm/shoulder shows a medium risk level after 211 minutes (3.5 hr). The postural risk for the hand/wrist is classified as "medium" after 300 minutes of work, while that of the arm/shoulder becomes medium after 211 minutes; also postural risk for the neck is classified as "medium" after 350 minutes of a task (5.8 hr of work). These findings can be useful for ergonomists and work designers, as they can modify the work to ensure low risk by controlling the exposure duration in order to secure the desired risk classification.

Table 2. Postural hazard assessment

Body part	Observed posture range	Daily exposure (8 working hr)	body part exposure %	Rhs	Risk Class
Neck	< 20	1.848	23.11%	1.5 after 264 min	Low
	20 - 90	2.706	33.83%	6 after 350 min	Medium
Hand & Wrist	0 - 15	3.163	39.55%	6 after 300 min	Medium
	> 15	1.395	17.45%	9 after 348 min	Medium
Arm & Shoulder	45 - 90	4.56	57%	6 after 211 min	Medium
				9 after 422 min	Medium

Table 3 summarizes the ergonomic risk scores and risk classification for the postural hazard, force/static load, hand/arm vibration, contact stress, repetition risk, and environmental risk factor. As it can be inferred from Table 3, workers are exposed to medium postural risk for the arm/shoulder, and hand/wrist. Ultimately it demonstrates an overall medium risk classification for the observed task.

Table 3. Resultant ergonomic risk scores

Hazard Score								
Body part	Postural hazard	Force /static load risk	Hand/ arm vibration	Contact stress	Repetition risk	Environmental risk	Resultant body part risk score	Risk class
Neck	6				1.5		6	Low
Arm/ shoulder	9		3				9	Medium
Hand/ wrist	9		3				9	Medium

Based on the above results work can be rotated or changed within safe limits to ensure low exposure to ergonomic hazards.

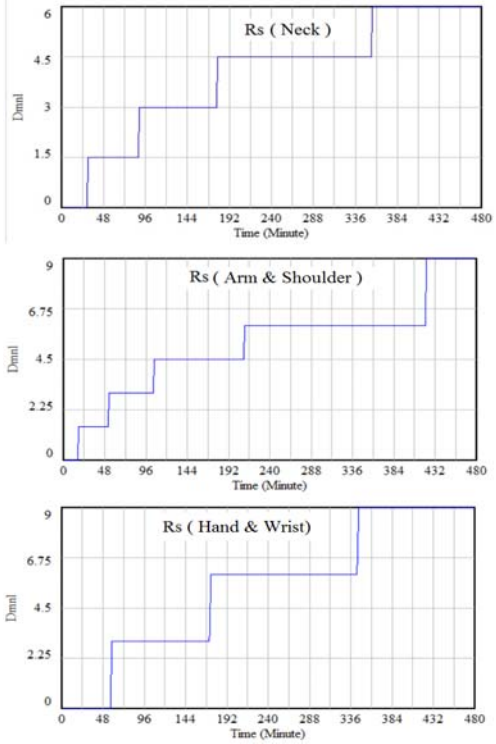

Figure 9. Resultant risk score of awkward posture including neck, arm/shoulders, and hand/wrist

5 Conclusion

The presented work shows an application of system dynamics (SD) to assess the ergonomic risk of residential construction tasks. The results obtained from the case study show that SD modeling not only can provide a graphical illustration, showing the logical links between cause and effects, but also increases the knowledge of how ergonomic risk can develop while performing task cycles. This can assist job designers and managers to have a clear understanding of possible ergonomic risks associated with the tasks as well as the major body parts affected. In order to address the ergonomic risks, recovery cycles should be designed in a way to avoid potential ergonomic risks. SD, as a powerful tool, can be used to explore several what-if scenarios caused by a range of variations in risk exposure, and can identify most contributing factors to potential ergonomic injury. While various factors, such as environmental and organizational, are typically assumed to be constant over time, they may be found to change as a result of their inter-relationships with other factors. Further investigation is thus recommended to address interactions among governing variables and their variations over time. The results identified in this study are expected to assist project work designers and ergonomists in controlling and assessing ergonomic risks, thereby leading to improved work efficiency, safety and reduced lost time injuries caused by WRMSDs.

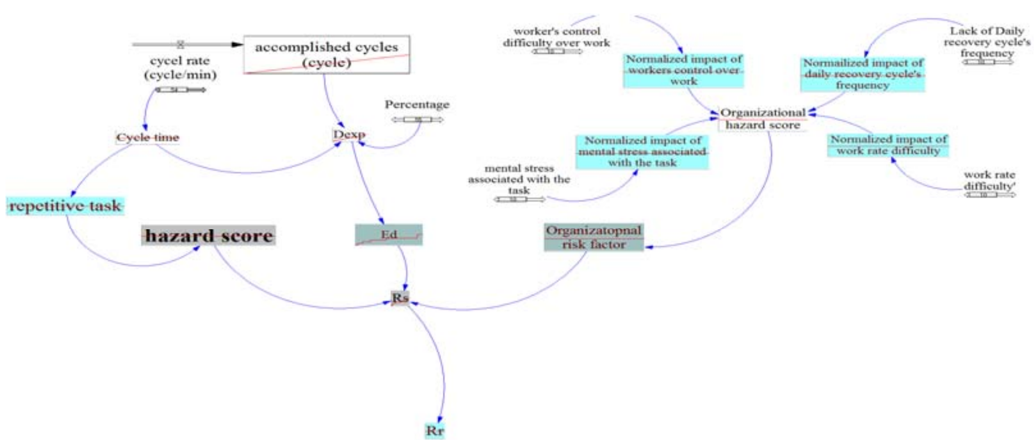

Figure 10, SD model of repetition risk factor

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