AMERICAN UNIVERSITY OF BEIRUT

# A DHM-ABM FRAMEWORK FOR CONSTRUCTION TASK ASSIGNMENT BASED ON WORKERS’ PHYSIOLOGICAL CAPABILITIES

by

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# AN ABSTRACT OF THE THESIS OF

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The construction industry has been constantly facing evolving and growing challenges and suffering from time delays and cost overruns. One key component of construction projects consists of labor productivity and its influencing factors such as ergonomics. In fact, applying ergonomics and understanding the interactions among workers and their assigned tasks have shown a decrease in workers' discomfort, a positive impact on productivity, a reduction in project costs, and an increase in value creation. As such, several studies have been conducted in an attempt to properly assign construction tasks and optimize the performance of crews. Some studies have only measured physiological capabilities, while other studies have linked the mental workload with the workers' mental capabilities. However, no study has yet been carried out to estimate physiological task workload and match it with the corresponding workers' capabilities.

Incorporating recent contributions from the fields of Digital Human Modeling (DHM) and Agent-Based Modeling (ABM), this research study develops an integrated framework for proactive performance control of construction crews through studying different task assignment techniques. More specifically, DHM is adopted to model different construction activities and generate physiological task demands, then ABM is used to map modeled tasks to construction workers and obtain performance values in terms of productivity and safety. A validation survey was administered among site engineers, and results highlighted the practicality and feasibility of the proposed hybrid framework and its potential in efficiently matching tasks with workers based on their physiological capabilities. The proposed system is sought to highly benefit contractors by helping them measure their workers' strengths and then optimally assign them to the right tasks.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Projects in the construction industry are known for their complex and uncertain nature, and their uncertainty is directly proportional to their complexity. They also have an inherent risk that affects both cost and schedule considerably (Wehbe and Hamzeh 2013). Any construction-related industry suffers from undue cost overruns, time delays, and prolonged contractual claims. Therefore, identifying and analyzing critical factors affecting construction productivity can lead to the development of better strategies to improve construction projects productivity (Liberda et al. 2003). As project's production efficiency can be measured by its labor productivity, many studies shifted their focus to studying factors affecting labor productivity and strategies to address them. In a study by (Rojas and Aramvareekul 2003), labor productivity factors that were mentioned repeatedly in the literature were included in a survey and categorized into four major categories: Management Systems and Strategies, Industry Environment, Manpower, and External Conditions. Among the Management Systems and Strategies, the authors stated that managers play an important role in adding or reallocating resources and that supervisors who lack proper skills can negatively affect the workers' performance. As for Manpower, worker experience was rated as the most relevant factor in this category. This factor highlights the significance of allocating the workers of good experience in their corresponding position. The aforementioned factors can be linked to ergonomics in terms of physical capabilities. In fact, applying ergonomics has shown a reduction in project costs associate with work-related injuries and an increase in value creation by improving the overall productivity and morale of workers (Curry and Meyer 2016). The major benefits of applying ergonomics can be summarized by the reduction of costs, increase in productivity, improvement of safety, and enhancement of quality (Damaj et al. 2016).

As ergonomics is a field of study that relates the human body to the machines, it can be used to address the issue of productivity in the construction industry by pinpointing the major ergonomic factors affecting the productivity and consequently resolving them.

Some studies have measured physiological statuses and capabilities, while other studies have linked the mental workload with the workers' applied mental capabilities. However, no study has yet been conducted to estimate physiological workload and match it with its corresponding physiological capabilities of the workers.

This research will address the physiological side of the task demands and applied capabilities. It aims to show the importance of construction task assignments based on task demands and the physiological capabilities of construction workers, where factors that are related to ergonomics such as inefficient resource allocation are addressed. Furthermore, in a real project, the simulation model coupled with actual physiological status monitoring can be utilized by project stakeholders, managers, or foremen to record their workers' physiological capabilities, insert them into the model as a database, and obtain real results on project performance in terms of productivity and safety. Such a framework can help improve project performance by taking appropriate task assignment into account.

## 1.2 Objectives and Research Framework

The objective of this research is to design a DHM-ABM framework for construction task assignment based on the workers' physiological capabilities and the tasks' demands. The specific objectives are:

- Study the effect of different construction tasks on the human body by modelling the tasks on a Digital Human Model (DHM) software.
- Develop a formula for the duration needed to complete different construction tasks by taking learning and fatigue into account.
- Present different possible methods for calculating "scores" for construction workers to evaluate their eligibility to perform the tasks.
- Present different assignment techniques that could be followed by foremen to assign workers to the appropriate task.
- Compare performance results of each assignment technique in order to select the optimal one.

This framework could also be used in real life projects, where contractors or foremen can use physiological status monitors (PSMs) to measure their workers' physiological capabilities, insert their results into the agent-base model as a database, and simulate different scenarios of different assignments techniques. This allows them to compare their performance under different circumstances and figure out the best resource allocation scenario.

## 1.3 Significance of the Research

As many studies have stated, research still lacks a study that links the physiological capabilities of constriction workers to the physiological demands of construction tasks. This research addresses this issue by developing a human body model and an agent-based model. The human body model is used to simulate construction activities and record their effects on the human body, such as fatigue, muscle strains, etc. The agent-based model is used to show the importance of matching physiological capabilities with task demands by utilizing the physiological demands obtained from the human body model and simulating various tasks with workers of different physiological capabilities. The aim is to compare the productivity of a crew under different assignment techniques. Furthermore, the simulation model coupled with actual physiological status monitoring can be utilized by project stakeholders, managers, or foremen to record their workers' physiological capabilities, save them as a database, insert them into the model, and obtain real results on project productivity and safety. Such a framework can help improve project performance by taking into account appropriate task assignment.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Ergonomics

The word “Ergonomics” originates from the Greek words ergon (work) and nomos (law). The precursors of ergonomics are Scientific Management by Frederick W. Taylor and Work Study by Frank and Lillian Gilbreth developed at the beginning of the twentieth century. Both promoted the belief that redesigning the method of performing work instead of using better machines or stronger workers could improve productivity. In the 1920s and 1930s, occupational psychology was developed by redesigning a job to make it easier to perform and setting a production standard, rate of pay, and a bonus scheme were introduced to push workers to produce higher than the standard. In the 1950s, around the same time when the modern history of ergonomics had emerged, the Sociotechnical Systems theory was introduced by Trist and Bamforth (Trist and Bamforth 1951) to study the interconnection between the organization of technology, the local environment, and the social organization and the importance of designing them in a compatible fashion to increase productivity and decrease psychological and pathological stresses. In the 1960s, 1970s, and 1980s, several programs emerged in some European countries in an attempt to humanize work and increase job satisfaction (Bridger 2009).

Ergonomics is the study of the interaction between humans and machines and the influencing factors of this interaction (Bridger 2009). It is an applied science that coordinates the design of systems and conditions with the capacities and requirements of the workers (Pao and Kleiner 2001). The main goal of the science of ergonomics is described as finding a “best fit” between workers on one hand and job conditions on the other hand. On a larger scope, it can also be described as examining human behavioral, psychological, and physiological capabilities and limitations (Jaffar et al. 2011). Most definitions view ergonomics as both a science and a technology (Wilson 2000). Ergonomics is drawn from several core sciences including engineering, physics, physiology, anatomy, and psychology. As stated by Bridger, whenever productivity problems are faced, engineers attempt to improve their machines, managers attempt to hire better-trained people, while ergonomists attempts to improve the interface, the task design, and the interaction between the user and the machine (Bridger 2009). Ergonomics looks at how physical abilities and limitations of the human body are related to work tasks, job environment, tools equipment, and materials (Albers and Estill 2007). Ergonomics is divided into three main domains: physical, cognitive, and organizational. While physical ergonomics is concerned with the biomechanical, anthropometrical, and physiological aspects of humans, cognitive ergonomics is concerned with the mental capabilities and skills of humans, and organizational ergonomics is concerned with organizational structures' effect on the productivity of the employees (Saba 2016). In this research, physical ergonomics is addressed.

The application of ergonomics in the workplace has proven to be of many benefits. The reduction of the costs associated with work-related injuries such as high medical expenses, related lost workdays, restricted workdays, workers' compensation costs, and cost per claim is one of the most prominent benefits of ergonomics (Curry and Meyer 2016; Damaj et al. 2016). Labor costs, turnover, and absenteeism are also decreased with the implementation of ergonomics in the workplace (Curry and Meyer 2016). Productivity is increased in the construction industry when ergonomics aspects are taken care of, such as using a variety of tools that can provide more convenient work conditions (Damaj et al. 2016). According to a case study by (Curry and Meyer 2016), productivity increased by 40% upon implementing ergonomics in the workplace. Safety is also improved as ergonomics aims at creating a safer environment by providing the appropriate tools for each task. According to (Hess et al. 2010), an increase of safety for masonry work was recorded by respondents to a survey. This study also recorded time savings as one of the advantages of applying ergonomics in masonry work. Another benefit is enhanced quality as workers grow motivated and dedicated to completing their work in a better work environment (Khani Jazani and Mousavi 2014).

### 2.2 Ergonomics in Construction and Work-Related Musculoskeletal Disorders

In spite of several attempts to improve construction methods, equipment, and tools, the construction industry still counts as a physically demanding industry (Gatti et al. 2014a). As the construction industry is predominantly physical in nature where activities are performed in unfavorable environments and at a fast pace, workers often require physical stamina (Inyang et al. 2012). In addition to prolonged standing, bending, stooping, and lifting heavy objects, several tools are required to be used in uncomfortable conditions to perform the tasks. Such factors can lead to injuries or physiological problems in the tendons, muscles, or nerves which might in turn lead to musculoskeletal disorders (Jaffar et al. 2011).

Work-related musculoskeletal disorders, as defined by the US Department of Labor, are injuries or disorders related to the muscles, nerves, tendons, joints, cartilage, and spinal discs that are associated with risk factors exposure in the workplace (Barbe and Barr 2006). In fact, the construction industry suffers from high rates of ergonomic injuries as the work station is not fixed and cannot be modified on a permanent basis (Schneider and Susi 1994). In the United States, 33% of all occupational injuries and illnesses that lead to absenteeism are due to work-related musculoskeletal disorders (WRMDs) (Wang et al. 2015). Furthermore, only 5% of the workforce are in the construction industry while 20% of all occupational fatalities and 9% of all disabling occupational injuries are due to the this industry (Abdelhamid and Everett 2000). Repetitive motion, high force exertion, and awkward body posture are all risk factors of WRMDs that construction workers are exposed to (Fang et al. 2015; Wang et al. 2015). Consequently, fatigue due to the mentioned factors may be associated with decreased motivation, vigilance, work capability and performance (De Vries et al. 2003). Moreover, whether such factors will or will not result in WRMDs depends on the intensity, duration, and frequency of the factors and not just their presence (Nath and Behzadan 2017). In the following paragraph, activities that can lead to WRMDs in the construction industry will be presented.

First, construction workers have an increased risk of injuries if they carry heavy loads, work on their knees, twist their hands or wrists, stretch to work overhead, use certain types of tools, or use vibrating tools or equipment (Albers and Estill 2007; Memarian and Mitropoulos 2016; Vachhani et al. 2016). Working at floor and ground-level such as when finishing slabs requires bending, kneeling, stooping, and squatting. Such postures can cause pain in the lower back or knees. Moreover, overhead work where workers reach up with one or both arms raised above their shoulders such as when drilling or finishing a drywall puts some stress on their shoulders and neck. Lifting, holding, and handling heavy materials or carrying them for long distances cause pain in the back, shoulders, neck, arms, hands, and wrists. Such activities require stooping downward or stretching upward to hold heavy objects. Hand-intensive work also affects the hands, wrists, and elbows when workers are required to use vibrating tools or grip objects forcefully. (Albers and Estill 2007). Table 1 shows examples, postures, and affected body parts of several types of work mentioned in Albers and Estill's study.

In another study by Jaffar et al., ergonomic risk factors were classified into three categories: biomechanical exposures, psychosocial stressors, and individual risk factors.

Ergonomic risk factors (ERF) were defined as situations that either already exist or are created intentionally or unintentionally whose consequences oppose the principles of ergonomics. Such consequences could have negative effects on the health and well-being of workers. ERFs were classified into seven different categories: repetition, force, awkward posture, vibration, contact stress, static loading, and extreme temperature (Jaffar et al. 2011). Repetition refers to performing the same motion excessively within a unit of time with little rest or recovery. A repetitive task is defined as a task that requires the involvement of a specific group of muscles repeatedly during a certain period, which results in the development of muscle fatigue (Li et al. 2017). Force is a physical effort required to accomplish certain movements or to maintain control of equipment. It causes stress on the muscles, tendons, and joints and leads to shoulder, neck, low back, forearm, wrist, and hand injuries. Additionally, vibration can be defined as a body movement that is made around a fixed point, whether regularly or randomly. Awkward postures are body positions that show significant deviations from their neutral position (Chen et al. 2017a). They can result from numerous activities such as leaning sideways, bending downward, reaching overhead, bending the wrist or the neck, or twisting part of the body (Jaffar et al. 2011). Contact stresses are impingements or injuries due to hard or sharp objects. They can injure the nerves and tissues beneath the skin and their effects can become worse if the contact area did not have much protective tissue. Extreme temperature refers to temperature that is either too hot or too cold, both of which can be dangerous to the human body. Finally, static loading is performing a task in one postural position for a long duration, which causes discomfort and tiredness (Jaffar et al. 2011). Table 2 shows a summary of tasks presented in (Spielholz et al. 2006) with their respective risk factors presented in (Jaffar et al. 2011), and the work types and damages presented in (Albers and Estill 2007).

Table 1: Examples, postures, and affected body parts of several types of work (Albers and Estill 2007)

| Work Type | Examples | Postures | Affected Parts |
|---|---|---|---|
| **Ground-Level** | Installing or finishing slabs, decks, floor coverings | Bending, stooping, kneeling, squatting | Lower back<br>Knees |
| **Overhead** | Drilling, driving fasteners, finishing a drywall | Lifting, holding, positioning heavy objects, raising hands above shoulders, tilting head, twisting body with arms in awkward/raised position, | Shoulders<br>Neck |
| **Lifting, Holding, and Handling Materials** | Handling heavy materials, carrying materials for long distances, stretching upward while holding heavy objects, stooping downwards to pick up heavy objects, twisting body when handling heavy objects, pushing or pulling heavy equipment | Stretching upward, stooping downward, twisting body all while carrying heavy objects | Back<br>Shoulders<br>Neck<br>Arms<br>Hands<br>Wrists |
| **Hand-Intensive Work** | Using vibrating tools, holding hard or sharp objects | Gripping forcefully, bending wrists when using them, moving wrist rapidly or repetitively | Hands<br>Wrists<br>Elbows |

Table 2: Tasks, postures, risk factors, work types, and damages of construction work (Albers and Estill 2007; Jaffar et al. 2011; Spielholz et al. 2006)

| Task Category | Task | Posture | Risk Factor | Work Type | Affected Parts |
|---|---|---|---|---|---|
| **Roofing** | Old roof removal | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | | High hand force with awkward posture and repetitive motion | R-A-C | H | Hands-Wrists-Elbows |

| | | | | | |
|---|---|---|---|---|---|
| | Installing new roofing | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | | High hand force with repetitive motion | R-C | H | Hands-Wrists-Elbows |
| | | Back bending | A | F | Lower back-Knees |
| | | Kneeling and squatting | A | F | Lower back-Knees |
| | | Moderate hand-arm vibration | V | H | Hands-Wrists-Elbows |
| | Loading roofing materials | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | Moving materials on the roof | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | Loading asphalt kettle | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | Installing roof insulation | Back bending | A | F | Lower back-Knees |
| **Residential Framing** | Floor deck installation | Back bending | A | F | Lower back-Knees |
| | Wall building | Back bending | A | F | Lower back-Knees |
| | Lifting/placing header beams | Heavy lifting | F | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | Lifting trusses and sheeted end gables | Heavy lifting | F | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | Lifting wall sections | Heavy lifting | F | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | Lifting material | Heavy lifting | F | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| **Commercial Carpentry** | Moving equipment | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | Moving material | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |

| | | | | | |
|---|---|---|---|---|---|
| | Installing deck from sheeting | Back bending | A | F | Lower back-Knees |
| | Constructing gang form | Back bending | A | F | Lower back-Knees |
| **Drywalling** | Stacking moving drywall | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | Hanging drywall | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | | High hand force with awkward posture and repetitive motion | R-A-C | H | Hands-Wrists-Elbows |
| | Taping, mudding, and sanding | High hand force with awkward posture and repetitive motion | R-A-C | H | Hands-Wrists-Elbows |
| | | Hands over head | A | O | Shoulders-Neck |
| **Masonry Hod-carrier** | Scaffolding construction | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | Mixing/Stocking mortar | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | | High hand force | C | H | Hands-Wrists-Elbows |
| | Stocking bloc | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | | High hand force | C | H | Hands-Wrists-Elbows |
| | Using grout hose | High hand force | C | H | Hands-Wrists-Elbows |
| | Consolidation | High hand force | C | H | Hands-Wrists-Elbows |
| | | High hand arm vibration | V | H | Hands-Wrists-Elbows |
| **Masonry Installation** | Saw cutting | Back bending | A | F | Lower back-Knees |
| | | Neck bending | A | F | Lower back-Knees |
| | Repetitive laying | High hand force with bent wrist | A-C | H | Hands-Wrists-Elbows |
| | | Highly repetitive motion | R | - | - |

| | | | | | |
|---|---|---|---|---|---|
| | Stocking tile/thinset | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |
| | Grouting | Highly repetitive motion with high hand force | R-C | H | Hands-Wrists-Elbows |
| | Installing floor tile | Kneeling | A | F | Lower back-Knees |
| | Installing wall file | Hands over head / elbows above shoulder | A | O | Shoulders-Neck |
| | | Kneeling | A | F | Lower back-Knees |
| | | Back bending | A | F | Lower back-Knees |
| | | Repeated hand impact | R-C | H | Hands-Wrists-Elbows |
| | | Highly repetitive motion with high hand force | R-C | H | Hands-Wrists-Elbows |
| | Installing ceiling tile | Hands over head / elbows above shoulder | A | O | Shoulders-Neck |
| | | Highly repetitive motion with high hand force | R-C | H | Hands-Wrists-Elbows |
| | Installing pavers | Kneeling | A | F | Lower back-Knees |
| | | Highly repetitive motion with high force | R-F | - | - |
| | | Heavy, frequent, and awkward lifting | R-F-A | L | Back-Shoulders-Neck-Arms-Hands-Wrists |

Risk factors: A=Awkward posture, C=Contact Stress, F=Force, R=Repetition, V= Vibration.

Work Types: F= Floor level, H=Hand-intensive work, L=Lifting materials, O = Overhead

## 2.3 Ergonomic Assessment Techniques

There are various methods and techniques to assess the ergonomics of workers. These techniques may be classified into four main groups (Inyang et al. 2012). The first group is checklists, surveys, and reports that mostly target individual risk factors such as certain injury types, cumulative trauma injuries, or awkward postures. They usually do not take other risks into consideration such as the exposure to vibration or temperature. The second group is observation-based methods such as Assessment of Repetitive Task (ART), Manual Handling Assessment (MAC), Ovako Working Analysis System (OWAS), Posture, Activity, Tools, and Handling (PATH), Rapid Upper Limb Assessment (RULA), Rapid Entire Body Assessment (REBA) (Hignett and McAtamney 2000), and Quick Exposure Check (QEC) (Li and Buckle 1998). All of the mentioned methods use visual assessment as a means of measurement. RULA, REBA, and PATH use videos and pictures, and REBA, MAC, ART, OWAS, and QEC use scoring sheets as a means of measurement (Valero et al. 2016). The third group is computer-based applications that are based on a combination of the first and second groups, in addition to artificial intelligence techniques. Some examples of computer-based applications are ErgoBuild (Nussbaum et al. 2009), ErgoCheck (Inyang and Al-Hussein 2011), Ergonom (Swat and Krzychowicz 1996), and a mathematical musculoskeletal shoulder model developed by (Dickerson et al. 2007). The fourth group for ergonomic assessment is direct measurement. Direct measurement includes all methods and techniques that measure the worker’s musculoskeletal activity and exposure to risk (Inyang et al. 2012). It is applied by attaching various types of sensors called Physiological Status Monitors (PSMs) to the subject’s body and is considered a highly accurate method for acquiring large quantities of data. PSMs will be discussed in the following section.

## 2.4 Physiological Status Monitors (PSMs)

Physiological Status Monitors (PSMs) are wearable non-invasive telemetry systems. They date back to the 1550s when goniometers were used clinically to measure and record linear movements and rotations. After the goniometers, accelerometers were developed in the 1940s, electro-goniometers were developed in the 1960s, and motion tracking systems were developed in the 1970s. Motion tracking systems provided more accurate results than their predecessors. Afterwards, electromyographic (EMG) systems were developed in the 1980s followed by Inertial Measurement Units (IMUs) that were developed in the twenty first century enabling researchers to measure acceleration, velocity, orientation, and the Earth's gravitational forces and magnetic fields (Valero et al. 2016).

There is a wide variety of different PSM systems available, and they all work autonomously and wirelessly. PSMs are used to monitor workers' physiological status without interfering with their ability to perform their dynamic or static activities. They can work for several hours and they can be either located in a fabric chest belt or garments or implanted on the subject's body (Gatti et al. 2013, 2014b). PSMs measure various parameters including heart rate (HR), breathing rate (BR), oxygen consumption, body postures, muscle electrical activity, motion sensors and so on (Cheng et al. 2013; Gatti et al. 2014b; a). Some PSMs even measure several parameters simultaneously.

In literature, several PSMs were used for different objectives and in various methods in the field of construction. In 2011, (Aghazadeh et al. 2011) studied the effect of varying amounts of lifted weight on upper extremity joint angles and muscle activity of the neck and shoulder by using EMG data. Later in 2012, they tested four methods of turning the hand wheel on a medium-sized gate valve at two different torque requirements and compared them in terms of efficiency, subjective ratings of perceived exertion, and EMG activity (Aghazadeh et al. 2012). In another study, (Greensword et al. 2012) developed a modified spike shoe by testing and comparing it to a regular spike shoe using EMG measurements to evaluate muscle activities. In 2013, (Gatti et al. 2013) tested three PSMs to assess their reliability in monitoring construction workforce during dynamic activities, while (Cheng et al. 2013) fused data on construction workers location using RTLS and physical strain using PSMs to suggest a new approach for automating remote monitoring of construction workers safety performance. In 2014, two PSMs were validated by comparing their heartrate (HR) and breathing rate (BR) measurements with gold standard laboratory instruments' measurements during static and dynamic activities (Gatti et al. 2014b); while another study investigated the relationship between physical strain by measuring HR and BR and task level productivity by calculating task level single factor productivity (Gatti et al. 2014a). In 2015, (Al-Qaisi and Aghazadeh 2015) compared accepted Maximum Voluntary Contraction (MVC) methods in the literature for the anterior deltoids and trapezius muscles to newly proposed MVC methods using EMG signals. They have also determined the effects of hand wheel height and angle on torque production capabilities and proposed recommended torque limits for valve systems (Al-Qaisi et al. 2015). Another study in 2016 studied human body motions that could cause WMSDs in construction-related activities and introduced a new system to detect and characterize unsafe postures of construction workers based on the measurement of motion data from wearable wireless IMUs (Valero et al. 2016). In 2017, predicted muscle forces from Human Body Modelling were compared with surface EMG (sEMG) data to assess muscle force and muscle fatigue development due to manual lifting tasks (Li et al. 2017), and an ergonomic solution was proposed and tested through PSMs by attaching a low height domestic stool to the pants of rebar workers to allow them to sit and work instead of squatting (Umer et al. 2017). An additional study quantified construction equipment operator physiological data by measuring the data and comparing it among different task and different operators (Shen et al. 2017). In 2019, (Breloff et al. 2019) assessed the impacts of work-related factors on the potential risk of developing knee MSDs due to residential roofing tasks in a laboratory setting, and (Al-Qaisi et al. 2019) determined the effects of hand wheel diameter and orientation on torque production capabilities, proposed recommended torque limits to accommodate operator physical strength, and explored gender differences in torque production capabilities.

In this study, heart and breathing rate-measuring devices in addition to electromyograms will be discussed.

### *2.4.1 Heartrate Measurement*

Muscular systems are indirectly related to heartrate. Heart rate (HR) and heart rate variation (HRV) are two of physiological measurements that count as indicators to a person's overall health condition (Kantor et al. 2001), as it has been proven in several field studies that monitoring HR is an effective method for measuring the physical strain (Gatti et al. 2013). Physically demanding activities lead to isotonic constructions, which in turn lead to an increase in heart rate (Cheng et al. 2013). It is therefore essential to measure the heartrate during the resting period and working period of construction workers in order to study the effect of the performed task on their physiological status. Heartrate can be measured by electrocardiograms (ECG). ECG sensors are connected to the garment's conductive fabric that is in direct touch with the skin. The heartrate is determined by collecting the heart's electric signal through the ECG. Some factors may cause inaccurate heartrate readings like the lack of moisture on a subject's skin that may produce movement artifact noise. Another factor causing inaccurate readings is electromyographic (EMG) noise. EMG signals are produced by the construction and relaxation of muscles. The magnitudes of these signals are quite similar to those of ECGs, which may affect ECG readings (Cheng et al. 2013).

### *2.4.2 Breathing Rate Measurement*

Breathing rate (BR) can be analyzed to assess a subject's cardiovascular health (Shen et al. 2017). PSMs determine the breathing rate by placing a belt around the subject's chest and measuring belt expansions and contractions (Gatti et al. 2014b). Another way to measure breathing rate is by using a stationary cardiopulmonary exercise system using breath-by-breath technology. This technology aids in monitoring respiratory functions and analyzing gases during a physical activity. The respiratory volume, breathing rate, oxygen intake, and carbon-dioxide output are measured. Breathing rate measurements should be recorded in relation to the subject's maximal and resting breathing rates, but maximal breathing rates require stress tests that might be unsafe for certain subjects (Abdelhamid 1999) and the literature does not include any reliable formula to estimate the maximal breathing rate with respect to the subject's characteristics. Therefore, the direct conversion of breathing rate to energy expenditure is not possible yet (Gatti et al. 2014a).

### *2.4.3 Electromyography (EMG) and Maximum Voluntary Contractions (MVC)*

Electromyography (EMG) is the recording and analysis of the signal produced from an active muscle and recorded by electrodes. EMG signals are bio-electric signals generated by muscles, and they have a wide range of applications including ergonomics, sport science, clinical diagnosis, and rehabilitation (Bi et al. 2019). They can be used to measure the kinematics of upper limb movements, which count as a human body's most vital and active parts. The EMG measurement process is as follows: A nerve fiber's branches activate the muscle fiber's motor endplate, which induces two depolarization waves that travel to a muscle fiber's ends. The EMG electrodes placed at some distance from the fiber record the electrical signals relate to the fiber depolarization (Hof 1984). The electrodes of the EMG measurement device must have a proper degree of selectivity which is a compromise between recording from the largest possible representative sample of the muscle's motor unit, and the smallest possible from neighboring muscles. They must also be free from interferences especially motion artifacts (Hof 1984). There are two types of EMG measurements: surface and intramuscular EMG. Surface EMG (sEMG) is the best choice for obtaining quantitative information about the muscle force, but it is limited to superficial muscles. However, if the muscle is not accessible through the skin surface, intramuscular EMG may be used. sEMG signals are altered based on the extent of muscle involvement during occupational work, and their analysis serve as a non-invasive method to predict the development of fatigue and muscle activity (Li et al. 2017).

A major drawback of EMG measurement and analysis is the fact that the data generated from the sEMG is relatively small in range microvolt, and it can be easily influenced by the way the sensors are placed and the condition of the subject's skin. Therefore, Maximum Voluntary Contraction (MVC) is one way to address this issue and to deal with the unwanted influence of the mentioned artifacts (Cahyadi et al. 2018). By definition, the value of MVC is the value is 100% full physical exertion. Other levels of physical exertion are expressed by the relative percentage with respect to MVC (Al-Qaisi and Aghazadeh 2015).

### 2.5 Digital Human Models

Having mentioned the prevalence of WRMDs in the construction industry, it is crucial to highlight the means of evaluating the conditions of the human body under specific circumstances. In order to describe the interactions of body components, monitoring, computing, and recording internal loads and moments acting on body segments is of high importance. In-vivo measurements are invasive methods and are inhibited by technical limitations (Li et al. 2017). Therefore, digital human models (DHMs) can be developed in order to estimate internal loads. Such models are non-invasive and offer a more feasible technique for analyzing muscle activity. They have been used in a variety of fields from automotive, to military, aerospace, construction, and more (Ma et al. 2010). Their applications span from task visualization and job safety evaluation to clinical assessments. Furthermore, they provide visualization information about body postures in addition to calculating the required forces and moments of body muscles and joints to complete a specific task. They also help in assessing the loading condition at the tissue-level. DHMs consider bones to be rigid segments whose degrees of freedom are actuated with attached muscles contractions (Li et al. 2017). They are three-dimensional anthropometric manikins that consist of interior and exterior models. The interior model is the human body skeleton, while the exterior model is the human body shape. Most DHMs have similar structure and functioning (Fritzsche 2010). DHM systems include Jack, 3DSSPP, Anybody, ErgoMan, Santos, and Safework. Safework is a highly integrated DHMs that was originally developed as a tool to investigate production ergonomics. Today, Safework enables setting up a human task simulation. Additionally, Jack can be used for production ergonomics as well. 3D Static Strength Prediction Program (3DSSPP) can be used for manual material handling, while Santos is typically used for military purposes (Abdel-Malek et al. 2006). Ergonomic assessment tools have been integrated into some simulation systems for computerization. 3DSSPP is one of the systems where RULA, OWAS, and similar tools were integrated for posture evaluation (Ma et al. 2010). Some shortcomings of DHMs include the fact that they do not provide appropriate methods for an overall ergonomics risk assessment (Fritzsche 2010). Safework, for example, only allows analyzing static scenes; the same issue is found in Jack. While Jack and Safework lack built-in inverse-dynamics capability, Anybody and similar software allow these computations to be possible in ergonomic applications (Wagner et al. 2007).

In the literature, DHMs were used for various objectives and in various applications. For example, in 1977, (Badler 1997) described the state-of-art of computation speed and control methods and argued for a strong connection between language and animation and describing current efforts in linking them. In 2002, a study reviews some of the researches to develop a set of human motion prediction model built by measuring several participants with a motion capture system (Chaffin 2002). In 2006, (Reed et al. 2006) presented a new approach to the control of human figure models and the analysis of simulated tasks embodied in an algorithmic framework developed in a Human Motion Simulation (HUMOSIM) laboratory. (Wagner et al. 2007) studied ergonomics simulation based on some ergonomics analysis and assessment elements by building an ergonomics virtual human that is a framework made up of several different models. Additionally, also in 2007, a study by (Honglun et al. 2007) studied ergonomics simulation based on some ergonomics analysis and assessment elements by building an ergonomics virtual human that is a framework made up of several different models. Moreover, in 2008, a study developed a novel memory-based simulation (MBMD) model as a general framework for simulating natural human motions for computer-aided ergonomic design (Park et al. 2008). (Ma et al. 2010) presented a study in 2010 proposing and extending a new muscle fatigue and recovery model in Digital Human Modelling (DHM) to evaluate joint fatigue in manual handling jobs. Furthermore, another study by (Fritzsche 2010) investigated how well ergonomics risk assessments on simulations with digital human models (DHM) match real-life assessments by evaluating work tasks in real life and as a DHM simulation. In 2017, (Li et al. 2017) compared predicted muscle forces from Human Body Modelling with sEMG data to assess muscle force and muscle fatigue development due to manual lifting tasks.

## 2.6 Simulation

Simulation by definition is a computer-based imitation of a process or system through which the user intends to understand its underlying behavior (Binhomaid 2019). As defined by (Shannon 1975), it is "the process of designing a computerized model of a system (or process) and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies for the operation of the system." When experimenting the real system is too time-consuming, expensive, or not practically possible, simulation allows researchers to experiment their process or system in a risk-free world. Simulation is effective in designing and analyzing complex processes under different conditions, as it helps address their dynamicity and uncertainty and compare several alternatives without having to alter the real system (Binhomaid 2019). The applications for simulation are numerous, varying from social systems, ecosystems, economics, project management, supply chains, airports, hospitals, to manufacturing, battlefields, computer hardware, control systems, etc…

(Teicholz 1963) was the first to propose simulation to study and reflect the complexity of construction systems and processes (AbouRizk et al. 2011). According to (AbouRizk 2010), the progress of simulation in academia occurred over three stages. The first stage was initiated by (Halpin 1977) by introducing CYCLONE, whose strength was in its simplicity and ability to model cyclic networks. Several enhancements if CYCLONE were introduced among the years. The second stage constituted of several simulation systems and applications during the early 1990s until 2000. Finally, the third stage witnessed a move toward integrating simulation with other tools including the four-dimensional computer-aided design (4D CAD) (AbouRizk 2010).

Simulation includes three different approaches: System Dynamics (SD), Discrete-Event Simulation (DES), and Agent-Based Modeling and Simulation (ABMS) (Zankoul et al. 2015). System Dynamics is suitable for strategic decision-making and policy analysis (Sterman 2000). Whereas DES represents the operation of dynamic and uncertain systems in a chronological sequence of events (Song and Eldin 2012). DES helps develop a surrogate of the real world, where changes occur at discrete instances in time (Abou-Ibrahim et al. 2019), and it has been used for modeling construction operations in several studies (Zankoul and Khoury 2016). ABMS is a new approach for modeling and simulating processes and systems with interacting autonomous agents (Chan et al. 2010). ABMS can be defined as agents, entities, or objects that continuously interact and make decisions autonomously within a simulation system and an environment in order to allow the examination of the effect of the adaptive behaviors of agents on the collective system patterns development (Barakat and Khoury 2016; Chen et al. 2013).

Agents in an agent-based model are autonomous, interacting, and heterogeneous, and they often represent people or groups of people (Macal and North 2011). They are autonomous in terms of being able to function independently within the environment it is present in and within its interactions with other agents. They are also interacting as they have certain mechanisms that describe the way they behave and interact with other agents, and they are modular or self-contained as they are identifiable individuals with a set of attributes, behaviors, and decision-making capabilities (Macal and North 2009).

An agent-based model has four aspects. The first aspect is its set of autonomous agents where each agent has a set of attributes and a set of specified behaviors. The attributes describe the state of the agent while the behaviors define how the agent reacts to changes in the environment. The second aspect is the set of agent relationships, each of which defines how the agent interacts with other agents on one hand and the environment on the other hand. The third aspect of an agent-based model is the environment in which the agents exist, defined by the set of global variables. The fourth and final aspect is the system that is composed of the three mentioned aspects i.e. the agents, their relationships, and their environment (Taylor 2014).

In the field of ergonomics, in 2001, (Lee et al. 2001) used simulation to outline considerations and initial directions associated with three emerging cognitive ergonomics issues that are identified in the study. Another study in 2015 was presented by (Ferjani et al. 2015) to compute realistic task durations in accordance with the fatigue of the workers by using multi-criteria analysis in order to find a balance between achieving short durations and avoiding congestion. The mentioned study can be considered similar to this research, but while they only took into account the fatigue of the operators, this study integrates various factors and capabilities. In 2016, a study developed a DES model including fatigue mitigation strategies such as rests, to estimate the physical demands and the muscle fatigue level. It also included a case study proving that excessive physical demands reduce performance of the workers (Seo et al. 2016).

## 2.7 Gaps in the Literature and Contributions

A study by (Mitropoulos et al. 2009) developed a construction safety cognitive model which proposes that task demands and applied capabilities determine the potential for errors and accidents. While discussing the role of production factors in construction safety, it was stated that a research by (Levitt and Samelson 1987) found that successful foremen analyze productivity issues within the crew and conduct new workers' orientation. This approach highlights the importance of proper workers' allocation within a crew. (Mitropoulos et al. 2009) also compared construction work to driving a vehicle. Task demands of driving a vehicle are related to the vehicle itself, the road, traffic conditions, and speed. Whereas the applied capabilities depend on the driver's competency, level of activation, and human factors such as fatigue which was proved to reduced applied capabilities. In construction terms, the worker's competency includes the skills and physical condition or strength. In a study of residential framing by the same research, it was found that foremen commonly intend to match the workers' abilities with the task demands by assigning the most experienced workers to the most difficult tasks.

To address the mentioned issue of inappropriate task allocation in construction activities, and in an attempt to match the workers' applied capabilities with task demands, a study by (Chen et al. 2017b) introduced the electroencephalography (EEG) approach to estimate the task "mental" workload or demand. The study states that improper task allocation results in mental and physical fatigue. While mental fatigue results in a reduction in efficiency and effort disinclination, physical fatigue results in a reduction in production rates. They conclude that for successful and proper task allocation, mental and physiological workload must be quantitatively assessed. Therefore, their study aimed at estimating the mental workload. Additionally, a study by (Ferjani et al. 2015) aimed at computing task durations taking into account workers' fatigue only. While several studies have measured physiological statuses and capabilities, no study has yet been conducted to estimate physiological workload and match it with its corresponding physiological capabilities of the workers.

# CHAPTER 3

# METHODOLOGY

Human body modelling was used to obtain physiological demands of construction tasks, while agent-based modelling was used to model physiological capabilities of construction workers, calculate different scores for each worker, and match each worker with the appropriate task based on different assignment techniques. The productivity and safety of the crew was calculated and compared among the different proposed techniques. The technique with the best results can be chosen. The followed steps are:

**1.** Choose several construction activities that require various body postures and affect different body parts.

**2.** Model each activity on Jack Human Modelling.

**3.** For each activity, record the ergonomic and physiological results such body joints torque, strength percent capable, and energy expenditure.

**4.** From the acquired data, build several ABMS models. Each model will follow a certain assignment criteria built in the code. All models will contain:

   **a.** Several workers with a learning rate and different experiences and body part strengths as agents.

   **b.** Different tasks with different task demands such as average durations, required number of workers, joints strength percent capable (SPC), body part torques, energy expenditure, and fatigue coefficient.

   **c.** The foreman agent who is responsible for assigning the workers to the appropriate tasks.

   **d.** Evaluate the productivity and safety of each model, and compare the results.

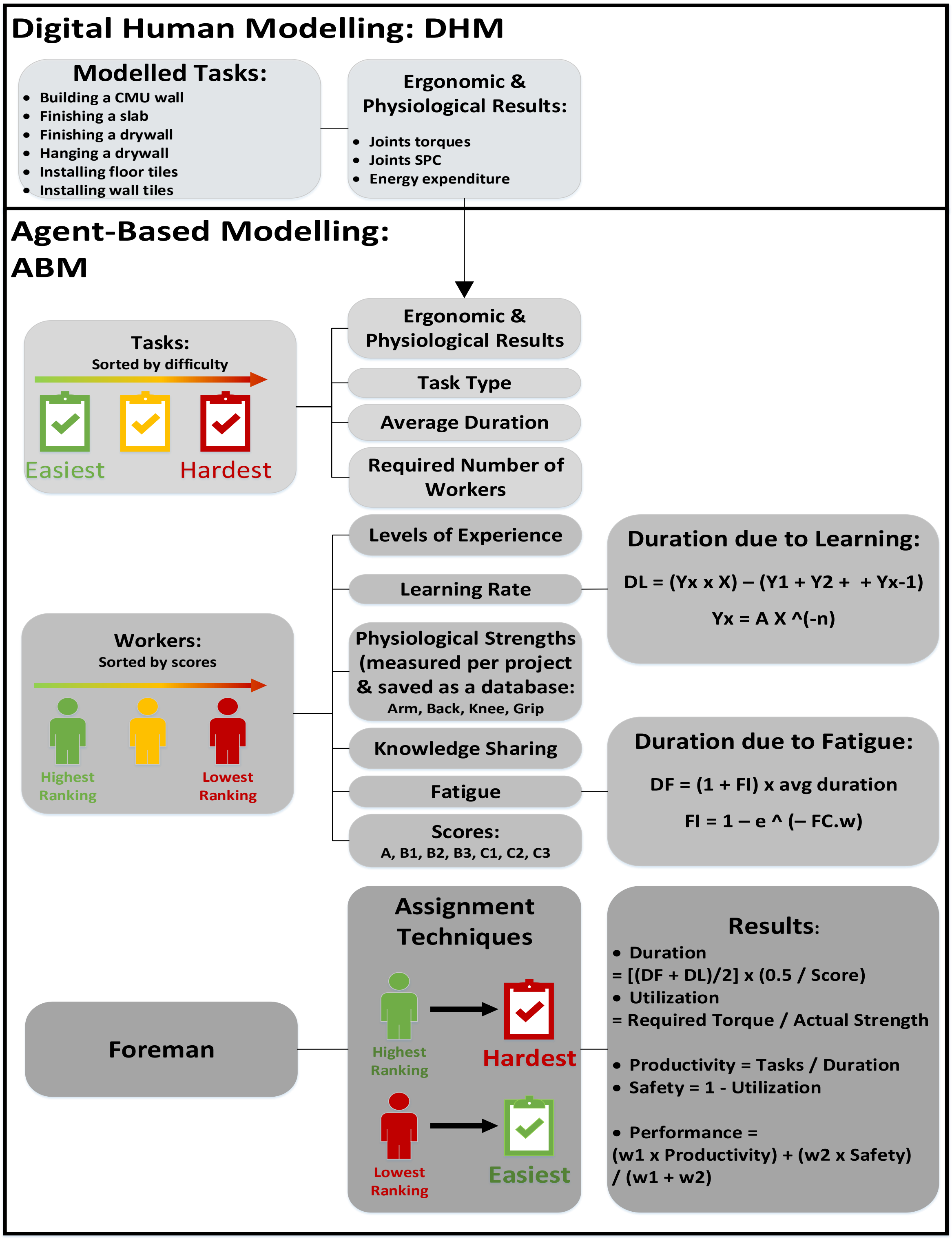


Figure 1 - Framework

# CHAPTER 4

# THE DIGITAL HUMAN MODELLING FRAMEWORK MODULE

## 4.1 Defining Tasks

### *4.1.1 Choosing Tasks*

In order to ensure adequate coverage of different types of tasks in the construction industry, the tasks included in this study fall under the different categories of tasks classified by previous researchers. Six tasks were chosen: two of which are "overhead", two are "ground-level", and two are "lifting, holding, and handling materials". Table 3 represents the chosen tasks and their corresponding categories.

Table 3 - Tasks Included in This Research

| Category | Lifting, Holding, and Handling Materials | Ground-level | Overhead |
|---|---|---|---|
| Tasks | 1. Building a CMU wall | 2. Finishing a slab | 3. Finishing a drywall |
| | 4. Hanging drywalls | 5. Installing floor tiles | 6. Installing wall tiles |

### *4.1.2 Task Data*

Each task's average production rate and required number of workers were obtained from RSMeans, which is North America's leading construction estimating database. It contains required crews, daily output, required labor-hours, and detailed cost estimates, for materials, labor, and equipment for almost all construction items (Mubarak 2020). Task data obtained from RSMeans and converted to the required units and values are shown in Table 4 below. The production rate in labor-hours per square foot (LH/SF) is obtained from RSMeans and then converted to the average required duration in hours. An area of 100 square meters is assumed for all tasks for consistency. The last two columns showing the required number of workers and the task duration (hours) are inserted into the agent-based model which will be discussed in the upcoming chapters.

Table 4 - Task Data Obtained from RSMeans

| Task No. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Task | Building a CMU wall | Finishing a slab | Finishing drywalls | Hanging drywalls | Installing floor tiles | Installing wall tiles |
| RS Means PR (LH/SF) | 0.1 | 0.2 | 0.08 | 0.1 | 0.08 | 0.08 |
| Area ($m^2$) | 100 | 100 | 100 | 100 | 100 | 100 |
| Area (SF) | 1076.4 | 1076.4 | 1076.4 | 1076.4 | 1076.4 | 1076.4 |
| Duration (LH) | 107.64 | 215.28 | 86.112 | 107.64 | 86.112 | 86.112 |
| Workers | 5 | 3 | 2 | 2 | 2 | 2 |
| Duration (hours) | 21.528 | 71.76 | 43.056 | 53.82 | 43.056 | 43.056 |

## 4.2 Modelling Tasks

Jack for human modelling was used to model and simulate the six different tasks under study. The steps required for performing each task were obtained and recorded from practitioners in order to be modelled.

### *4.2.1 Building a CMU Wall*

According to practitioners, the first step for building a CMU wall is bringing several blocks closer to the location where the wall will be built. Afterwards, the mixed mortar in a bucket is placed right where the first block will be placed using a knife. Then, the first block is placed, and the same steps are repeated until the line of blocks is in place. Afterwards, more blocks are brought closer, and the steps are repeated until the whole wall is built. These steps were modelled precisely in Jack, where each block was given a weight of 14 kilograms.

#### *4.2.2 Finishing a slab*

Finishing a slab requires many tools and several different steps. The first step is using a screeder, which can be a 2'x4' wood plank, to screed the surface of the concrete slab after pouring the concrete. Next, a wood float commonly known as a bull float is used to flatten the surface of the slab. After the wood float, an edge trowel is used to give the edges of the slab a neat appearance. Then another wood float is used to remove any lines created from the other tools. A steel trowel or a "fresno" is then used to give the concrete slab a nice finished appearance. Finally, a steel hand trowel is used to smooth out everything on the slab. Each tool was carefully built in Jack, and each step was modelled and performed by the manikin to obtain accurate ergonomic results. Figure 2 shows a snapshot of the task that was modeled on Jack by mimicking the movements of a real construction worker.

#### *4.2.3 Finishing a drywall*

Finishing drywalls also requires several tools and movements that need to be accurately modelled. The first step is using a screw driver to screw in any protruding screws. Next, a 5-inch knife is used to load the pan with mud from the bucket. Using the same knife, mud is applied to all joints in the drywall. Afterwards, the joints are carefully taped using a paper drywall tape. In order to ensure that the tape is not protruding, the 5-inch knife is used to apply pressure to the tape. Using an 8-inch knife, the pan is loaded with mud which is applied to the joints once again. Increasing the size of the knife gradually helps in applying mud to a larger area every time. The knife is then used to "feather" the edges, or in other words, to remove any excess mud from the joints. The same steps are then repeated using a 12-inch knife. It is also used to feather any imperfections in the joints. Finally, a drywall sanding pole is used to sand the drywall.


Figure 2 - Task 2 Modelled In Jack

#### *4.2.4 Hanging a drywall*

In order to hang a drywall, adhesive is applied to the studs where the drywall sheets will be installed in order to prevent popped nail heads. The sheets should be cut according to the wall size. Then the first sheet is held against the ceiling and the corner, and a few nails are driven in to hold the sheet in place. The same steps are repeated for the rest of the sheets. Screws are then driven in about 16 inches apart along all studs.

#### *4.2.5 Installing floor tiles*

After bringing the tiles to the location where they will be installed, the center of the floor is located and the middle tiles are placed. Spacers are used between the tiles to ensure proper distances between them. One or two of the placed tiles are removed to apply grout underneath. After placing the tiles above the grout, some pressure is applied to secure them into position. The same process is repeated until all tiles are placed with grout underneath. In the model, each tile is given a weight of 3 kilograms.

#### *4.2.6 Installing wall tiles*

The first step for installing wall tiles is using a knife to apply grout to a small portion of the wall where the first few tiles will be placed. Each tile is then placed and some pressure is applied to secure it into position. The same steps are repeated until all of the tiles are in place. In the model, each tile is given a weight of 3 kilograms.

### 4.3 Obtaining the results

After each task is modelled, several reports are obtained. The first report is the Metabolic Energy Expenditure (MEE). In this report, the metabolic cost in kilocalories for each movement is recorded. At the end of the report, the task component is calculated along with the postural component. The task component represents the kilocalories needed to perform the tasks, while the postural component represents the kilocalories needed for the required postures. The total metabolic cost is then calculated, and the energy expenditure rate in kilocalories per minute (kcal/min) is shown.

In addition to the MEE report, the Static Strength Prediction (SSP) report is obtained. SSP helps evaluate the percentage of the population that has the strength to perform a task based on posture, exertion requirements, and anthropometry. It evaluates jobs in real-time and provides joint torque and angle data, in addition to feedback on mean strengths and percent capabilities. In this research, the strength percent capable (SPC) and joint torques are used. Since SPC represents the percentage of the population with enough strength to perform the job, a conservative approach would be focusing on the minimum SPC per joint per task. However, for joint torques, maximum values were of higher importance. Physiological data for each task obtained from Jack is sorted in Table 5 shown below.

Table 5 – SPC, Joint Torque, and Energy Expenditure Results from Jack

| **Task No.** | **1** | **2** | **3** | **4** | **5** | **6** |
|---|---|---|---|---|---|---|
| **Task** | Building a CMU wall | Finishing a slab | Finishing a drywall | Hanging drywalls | Installing floor tiles | Installing wall tiles |
| **Elbow SPC** | 99 | 100 | 100 | 80 | 100 | 100 |
| **Shoulder SPC** | 98 | 99 | 99 | 60 | 99 | 99 |
| **Humerus SPC** | 8 | 99 | 99 | 55 | 99 | 99 |
| **Trunk SPC** | 93 | 97 | 80 | 96 | 91 | 99 |
| **Hip SPC** | 87 | 91 | 84 | 87 | 94 | 95 |
| **Knee SPC** | 27 | 24 | 34 | 50 | 55 | 67 |
| **Energy Expenditure** | 10 | 5.8 | 6 | 5 | 8 | 6 |
| **Req. Humerus Torque** | 14 | 2 | 2 | 22 | 3 | 4 |
| **Req. Trunk Torque** | 216 | 141 | 189 | 210 | 133 | 122 |
| **Req. Knee Torque** | 180 | 160 | 183 | 174 | 127 | 153 |

## 4.4 Results Validation

A study by Abdelhamid and Everett 1999 collected physiological measures of energy expenditure along with other data for an eight-member concrete slab placing and finishing crew performing actual construction work (Abdelhamid and Everett 1999). Workers number 2 and 8 were responsible for finishing cement, and their estimated energy expenditure results were 5.34 and 6.19 $kcal.min^{-1}$ respectively. Averaging both results gives 5.78 $kcal.min^{-1}$, which validates the 5.8 $kcal.min^{-1}$ value for Task #2: Finishing a slab obtained from Jack.

Another study by the same authors (Abdelhamid and Everett 2002) estimated the average energy expenditure for hanging drywalls (with lifting) to be around 4.64 $kcal.min^{-1}$, also close to the 5 $kcal.min^{-1}$ value obtained from Jack for Task # 4: Hanging drywalls.

While no studies were found to estimate the energy expenditure of the rest of the tasks in this study, a survey will be conducted when possible to validate them from the construction workers' perspective.

# CHAPTER 5

# THE AGENT-BASED MODELLING AND SIMULATION FRAMEWORK MODULE

The model is built in Anylogic and includes three agents: tasks, workers, and a foreman.

## 5.1 Task Agent

As already mentioned, six tasks are included in this study. The six tasks are: building a CMU wall, finishing a slab, finishing a drywall, hanging drywalls, installing floor tiles, and installing wall tiles. The task agent contains a statechart where each task moves from being unavailable to available at a certain rate. Each task type has several parameters that are shown in Table 6.

Table 6 - Task Agent Parameters

| Parameter | Source | Value |
|---|---|---|
| Average Duration | RSMeans | - |
| Required Number of Workers | RSMeans | - |
| Strength Percent Capable (SPC) of the: wrist, elbow, shoulder, arm, back, hip, and knee | Jack | - |
| Required Joint Torques of the arm, back, and knee | Jack | (Torque – min) / (max – min)<br>max = max torque & min = min torque |
| Energy Expenditure (EE) | Jack | |
| Fatigue Coefficient (FC) | - | (EE – min) / (max – min)<br>max = 12.5 & min = 2 (Roja et al. 2006) |
| Most Affected Body Part | Jack | - |
| Average SPC | - | ∑(SPC of all joints) / 7 |
| Minimum SPC | - | Minimum value of all joints SPC |
| Average SPC of the arms, back, and knees | - | (Arms SPC + Back SPC + Knee SPC) / 3 |
| Minimum SPC of the arms, back, and knees | - | Minimum value of the arm, back, and knees SPC |

The production rate values obtained from RSMeans and the values inserted into the model are shown in Table 7.

Table 7 - Production Rates, Durations, and Required Number of Workers

| Task No. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Task | Building a CMU wall | Finishing a slab | Finishing a drywall | Hanging drywalls | Installing floor tiles | Installing wall tiles |
| RSMeans PR (LH/SF) | 0.1 | 0.2 | 0.08 | 0.1 | 0.08 | 0.08 |
| Area (m2) | 100 | 100 | 100 | 100 | 100 | 100 |
| Area (SF) | 1076.4 | 1076.4 | 1076.4 | 1076.4 | 1076.4 | 1076.4 |
| RSMeans Duration (LH) | 107.64 | 215.28 | 86.112 | 107.64 | 86.112 | 86.112 |
| Workers | 5 | 3 | 2 | 2 | 2 | 2 |
| RSMeans Duration (hours) | 21.528 | 71.76 | 43.056 | 53.82 | 43.056 | 43.056 |

Once a task becomes available, a message containing the type of the available task is sent to the foreman who is in charge of assigning workers to each task. Figure 3 shows the statecharts and parameters of the Task agent.

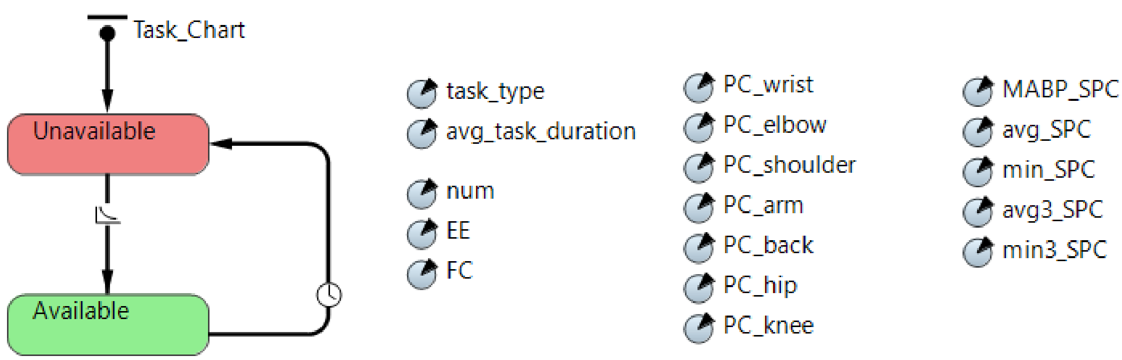


Figure 3- Task Agent

## 5.2 Foreman Agent

Once the foreman receives a message from any of the six tasks, he moves from the “Idle” state to the “Collecting” state, saves the task data of the task at hand, and moves back to the “Idle” state to wait for another message from the tasks. When the task data is saved, the task is also added to a collection where it is sorted based on its “difficulty”. The task with the lowest average SPC value is considered the most difficult task, while that with the highest average SPC value is considered the easiest. Once three tasks are at hand, the foreman moves to the “Evaluating” state and sends a “Get Scores” message to all workers. After all scores are calculated, the foreman moves to the “Assigning” state where he sends a “Start Working” message to the appropriate workers to be assigned to the tasks at hand. Appropriate workers are chosen based on their scores or their strongest body parts, in addition to the task’s difficulty. The details of the assignment techniques will be discussed in the following sections. Figure 4 shows the statechart and the parameters of the Foreman agent.

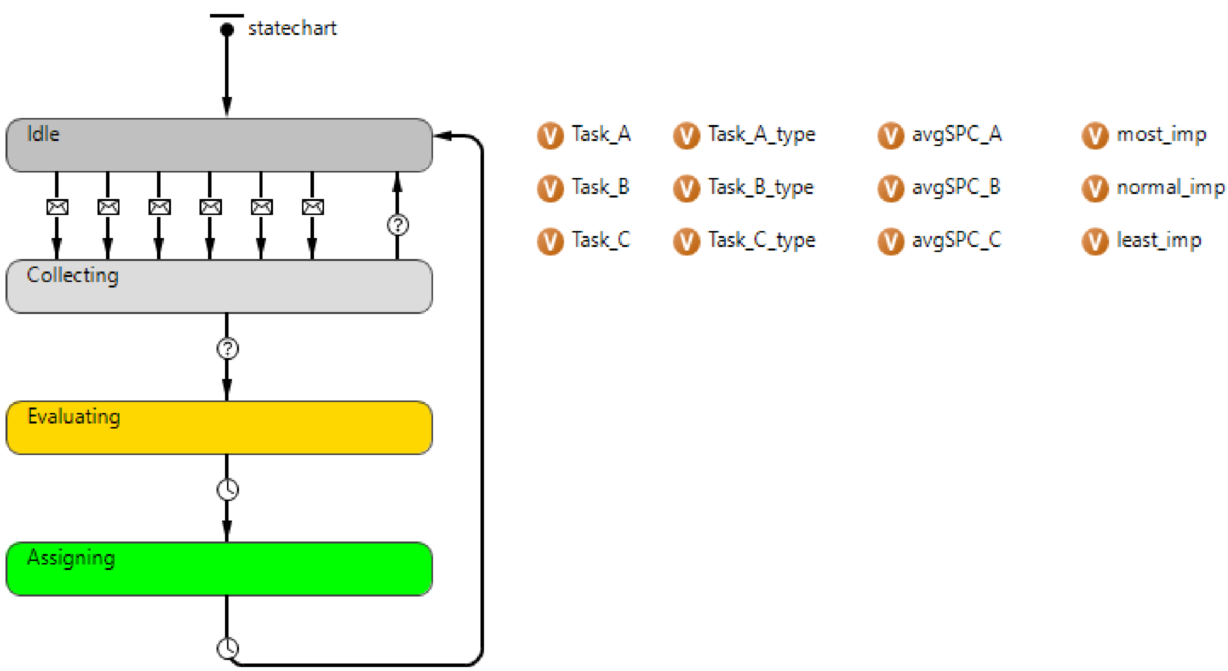


Figure 4 - Foreman Agent

## 5.3 Workers Agent

This model includes a population of sixteen workers, since the sum of the required number of workers of all six tasks is sixteen. On startup, each worker is given grip, arm, back, and knee strengths from a normal distribution. Each worker is also given an "experience level" for each task, which is a random value from 0.1 to 1. All workers have a learning rate that is assigned by the user at the beginning.

All workers are in the "Idle" state until a "Get Scores" message is received from the Foreman. This message triggers a transition where all workers move to the "Assessing" state, and all of their scores are calculated. Afterwards, the workers are added to several collections where they are sorted according to their scores. The higher the score, the higher the rank. Once all workers are sorted in the collections according to their scores, only those who receive a "Start Working" message from the Foreman move to the "Working" state. Others return to the "Idle" state. The duration needed by the worker to perform each task is a function of the average task duration, the learning rate, and the worker's fatigue. The exact formula for the durations will be shown in the following sections. The productivities and arm, back, and knee utilizations are calculated for each worker. Figure 5 shows the statechart of the Workers, and Figure 6 shows their parameters.

Moreover, whenever several workers are working simultaneously on the same task, the less knowledgeable worker will gain more experience from the more knowledgeable one. This phenomenon is called "Knowledge Sharing" or "Transferred Experienced", and it is the voluntary dissemination of acquired skills and experience among workers (Law and Ngai 2008). Several studies have shown that construction workers receive much of their experience and knowledge while performing the tasks, and that as they gain experience, the time needed to accomplish their tasks decreases (Kiomjian et al. 2020). Therefore, in this model, the experience of the less-knowledgeable worker increases by 0.1 whenever a more knowledgeable worker is performing the same task.

Enhanced experience = original experience x 1.1

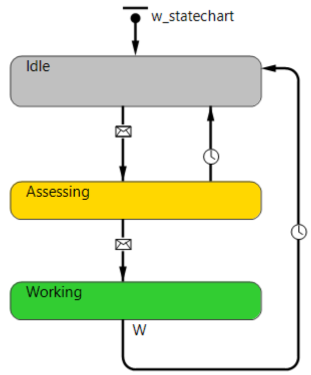


Figure 5 - Workers Statechart

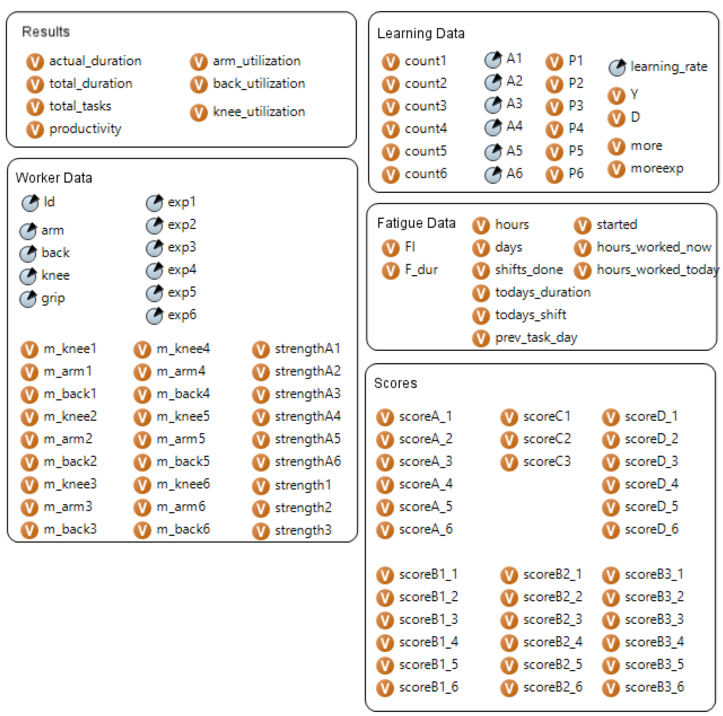


Figure 6 - Workers Parameters and Variables

## 5.4 Duration Calculation

The time needed to perform each task varies according to the strength and fatigue of the worker, the task, and the learning curve.

### *5.4.1 Duration Based on Learning*

In this research, Wright's learning model is used. Wright's learning formula is:

$Y = A X^{-n}$ (Wright 1936)

where Y = cumulative average time required to perform a repetitive unit

A = the time of the first unit

X = repetition number

n = learning rate $0.1 < n < 1$

Since Y represents the cumulative average time, then the time required to perform the task for the $X^{th}$ time is:

$$D_{Lx} = (Y_x \times X) - \sum \text{previous durations} \quad (1)$$

### *5.4.2 Duration Based on Fatigue*

Since human factors play an important role in affecting the productivity of the workers, studies have shown that fatigue causes a significant increase in task durations (Ferjani et al. 2015). One way to take the workers' fatigue into account while calculating the expected durations is by including the Fatigue Index (FI) of the worker and the Fatigue Coefficient (FC) of the task. According to Ferjani et al. and in accordance with (Konz 1998), the fatigue of a worker can be approximated using the following indicator:

$$I = 1 - e^{-d.w} \quad (2)$$

where d = "penibility" coefficient and w = the time carried out by the worker to process their previously assigned tasks since the beginning of the shift until the current time.

The work "penibility" is most probably derived from the French word "pénibilité" which means painfulness. Therefore, in this research, the "penibility" coefficient or d will be replaced with the Fatigue Coefficient (FC) which is derived from the energy expenditure results obtained from Jack as shown in Table 6. Therefore, equation (2) can be replaced with equation (3):

$$FI = 1 - e^{-FC.w} \quad (3)$$

Afterwards, Ferjani et al. suggest the computation of duration T' by taking the fatigue into account:

$$T' = (1 + I) \times T \quad (4)$$

where T = theoretical time

In this research, equation (4) will be replaced with equation (5) to calculate the duration $D_F$ by taking fatigue into account by using the parameters of the built agents:

$$D_F = (1 + FI) \times \text{average duration} \quad (5)$$

### *5.4.3 Duration Based on Learning and Fatigue*

In order to calculate the duration by taking the worker's learning and fatigue into consideration, a formula for duration D was developed as an average of both durations:

$$D_{LF} = \frac{DL+DF}{2} \quad (6)$$

### *5.4.4 Final Duration*

The final actual duration will be a function of the worker's score in addition to the learning and fatigue that are already accounted for.

$$D = DLF \times \frac{0.5}{S} \quad (7)$$

where S = the score of the worker $0.1 < S < 1$

According to the formula, when the worker has the highest possible score (score = 1), his duration will be halved. When the worker has the lowest possible score (score = 0.1), his duration will be multiplied by 5. However, if the worker has an average score (score = 0.5), the duration will not be affected.

There are eight different ways to calculate score S, all of which will be discussed in the following section.

## 5.5 Scores Calculation

In order to decide on the best assignment technique to be followed, several methods to calculate the workers' scores are suggested. The scores are divided into two categories. The first category includes scores that represent the strength and the experience of the worker, the second category includes scores that represent only the strength, while the third category includes the scores that represent only the experience of the worker. Score A is the only score that is dependent on the task demands, where the strength of the workers obtained from physical strength tests are divided by the required joint torques of the task demands. The calculation of each score is shown below:

### *5.5.1 Represent strength and experience:*

- Score A = (Strength + Experience) / 2 $0.055 < A < 1$

  Strength = (m_knee + m_arm + m_back) / 3

  m_knee = knee strength / (required knee torque x 10)

  m_arm = arm strength / (required arm torque x 10)

  m_back = back strength / (required back torque x 10)

- Score B1 = (Strength + Experience) / 2 $0.1 < B1 < 1$

  Strength = (grip strength + arm strength + back strength) / 3

- Score B2 = (Strength + Experience) / 2 $0.1 < B2 < 1$

  Strength = (knee strength + arm strength + back strength) / 3

- Score B3 = (Strength + Experience) / 2 $0.1 < B3 < 1$

  Strength = (knee strength + grip strength + arm strength + back strength) / 4

#### *5.5.2 Represent only strength:*

- Score C1 = (grip strength + arm strength + back strength) / 3 $0.1 < C1 < 1$
- Score C2 = (knee strength + arm strength + back strength) / 3 $0.1 < C2 < 1$
- Score C3 = (knee strength + grip strength + arm strength + back strength) / 4 $0.1 < C3 < 1$

As shown, some scores are related to the grip, arm, and back strengths of the workers, while others are related to the knee, arm, and back strengths of the workers. The grip strength measurement was originally inspired from a study by Jackson et al. who developed a strength index calculate by adding the isometric grip, arm lift, and torso lift strength tests (Jackson et al. 1992). Their research addressed specific industrial tasks, however, DHM results in this study showed some significant values for the knee, which was the incentive behind proposing additional indices or scores. Therefore, some of the proposed scores include only the grip strength, only the knee strength, or both the grip and knee strengths.

### 5.6 Assignment Techniques

In order to study the performance of a construction crew under different circumstances, and due to the importance of matching physiological capabilities to task demands, several assignment techniques are proposed in this research. Some techniques address the required torques, while others address the average or minimum SPC of all or certain joints. In an attempt to study as many techniques as possible, a matrix including all scores and task demands is developed. Rows represent the workers' calculated scores, and columns represent task demands. The matrix is represented in Table 8. A first simulation will be run to study the performance of a crew were random workers are assigned to random tasks. This simulation will act as a control. Another simulation will be run to study the performance of a crew where the workers with the strongest specific body part, arms for example, are assigned to the task that requires the highest arm strength. These two simulation runs will not include the calculated scores. The rest of the simulations will be run to study different combinations of scores and task demands. The different task demands that will be addressed are the average and minimum SPC of all joints, the average and minimum SPC of only the arms, back, and knees, and the energy expenditure. The reason that the average and minimum SPC of the arms, back and knees will be used is that according to the results obtained from Jack, these three body parts showed the lowest SPC values indicating that a low percentage of the population have enough arm, back, and knee strength to perform the tasks at hand. Research has also shown that the mentioned body parts are the most injured body parts in the construction industry. For example, floor tilers kneel down all day to set the tiles, while leads to knee and back postural stresses (Everett 1999). According to the Everett 1999, lower back pain, cervicobrachial disorders, and upper extremity cumulative trauma injuries are the most commonly reported injuries in the construction industry.

The technique with the best performance will be identified. A total of 37 simulation runs will be performed.

Table 8 - Proposed Assignment Techniques

| Tasks / Workers | Random | SPC of Most Affected Body Part | Avg. SPC | Min. SPC | Avg. SPC of 3 Major Joints | Min. SPC of 3 Major Joints | Energy Expenditure |
|---|---|---|---|---|---|---|---|
| Random | 1 | | | | | | |
| Strongest Body Part | | 2 | | | | | |
| Score A | | | 3 | 4 | 5 | 6 | 7 |
| Score B1 | | | 8 | 9 | 10 | 11 | 12 |
| Score B2 | | | 13 | 14 | 15 | 16 | 17 |
| Score B3 | | | 18 | 19 | 20 | 21 | 22 |
| Score C1 | | | 23 | 24 | 25 | 26 | 27 |
| Score C2 | | | 28 | 29 | 30 | 31 | 32 |
| Score C3 | | | 33 | 34 | 35 | 36 | 37 |

## 5.7 Performance Measurement

The results of the simulations run include two aspects: productivity and safety.

### *5.7.1 Productivity Measurement*

Since the aim of every contractor is to optimize the productivity of the crew, productivity measurement is usually one of the most common Key Performance Indicators (KPIs). In this research, productivity will be measured as the number of tasks per week. Since each task has a unique average duration, the actual value of the productivity is not the main concern. Instead, the difference between the productivities of the same crew following different assignment techniques is the result of major significance.

Productivity = tasks completed / total duration

### *5.7.2 Safety Measurement*

From an ergonomic point of view, the interaction between several factors may come into play to result in the safe performance of a task (Gagnon and Smyth 1991). Such factors include the weight of a handled object, the nature of the task, the working height, …

Safety can also be measured by the strength utilization ratio. Some studies use the Muscular Utilization Ratio (MUR) to estimate the relative involvement of some muscles, or their percentage of maximal strength (Milot et al. 2007; Nadeau et al. 1996). It reflects how severely the joint is being needed throughout the motion, where the higher the value, the larger the muscular demand.

$$\text{MUR} = \frac{\text{WM x 100}}{\text{MPM}} \tag{8}$$

where WM = mechanical demand

MPM = maximal potential moment

In this research, body part utilizations will be calculated as follows:

Utilization = (required body part torque / worker's body part strength) x 100 (9)

The numerator represents the task demand, and the denominator represents the maximal potential strength of the worker. Therefore, the arm, back, and knee utilizations of all workers are calculated in the agent-based model.

### *5.7.3 Performance Measurement*

The overall performance measurement can be calculated by assigning a weight to each result according to equation 10.

$$\text{Performance} = \frac{\sum \text{W.R}}{\sum \text{W}} \qquad \text{(Stobrawa et al. 2018)} \tag{10}$$

Where W = the assigned weight of the result

R = the result (productivity and safety)

In this study, both results were given equal weights of 0.5, so the equation used was the following:

$$\text{Performance} = \frac{(0.5 \text{ x productivity}) + (0.5 \text{ x safety})}{1} \tag{11}$$

# CHAPTER 6

# SIMULATION RESULTS AND DISCUSSION

Thirty-seven simulation runs were performed. Each run included a score and a specific task demand as shown in Table 8 above. Productivities, durations, and body part utilizations were recorded. The productivities and utilizations were then normalized, and the performance was calculated. The results are shown in Table 9.

The productivity, duration, arm utilization, back utilization, and knee utilization are raw mean values directly obtained from Anylogic. The average utilization is the average of the three body part utilizations.

$$\text{Average Utilization} = \frac{\text{Arm Utilization}+\text{Back Utilization}+\text{Knee Utilization}}{3} \qquad (12)$$

The normalized productivity and normalized utilization are obtained by using the following normalization formula:

$$\text{Normalized value} = \frac{(\text{value}-\text{minimum})}{(\text{maximum}-\text{minimum})} \qquad \text{(Yu et al. 2009)} \qquad (13)$$

The minimum is the lowest value of the productivity or utilization among all techniques, and the maximum is the highest value.

Since good performance is represented by high productivity and low utilization, the normalized utilization value was subtracted from 1 to obtain the complementary percentage. This way, performance is a function of productivity and the complement of utilization, which represents safety. The results are color-coded based on their values. For example, the highest productivity value was colored in green, and the lowest productivity value was colored in red. Average values are in yellow, and the rest are colored in shades between green, yellow, and red.

Table 9 - Simulation Results

| # | Score | Task Demand | Prod. | Duration | Arm Util. | Back Util. | Knee Util. | Avg. Util. | Norm. Prod. | Safety (1 - Norm. Util.) | Overall | Prod | Safety | Overall |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **Random** | **Random** | 2.7 | 46.15 | 112.42 | 154.83 | 154.36 | 140.54 | 0.00 | 0.52 | **0.259** | | | |
| **2** | **Strongest Part** | **Most Affected Part SPC** | 6.9 | 19.84 | 80.32 | 159.35 | 141.62 | 127.10 | 1.00 | 0.65 | **0.824** | | | |
| **3** | | **avg SPC** | 5.21 | 23.93 | 234.2 | 190.52 | 148.19 | 190.97 | 0.60 | 0.03 | **0.315** | | | |
| **4** | | **min SPC** | 5.15 | 24.63 | 147.28 | 144.13 | 146.33 | 145.91 | 0.58 | 0.47 | **0.525** | | | |
| **5** | **A** | **avg 3 SPC** | 5.29 | 22.84 | 195.25 | 181.2 | 139.86 | 172.10 | 0.62 | 0.21 | **0.416** | 0.601 | 0.24 | 0.419 |
| **6** | | **min 3 SPC** | 5.15 | 24.63 | 147.28 | 144.13 | 146.33 | 145.91 | 0.58 | 0.47 | **0.525** | | | |
| **7** | | **EE** | 5.33 | 24.08 | 229.47 | 206.08 | 147.68 | 194.41 | 0.63 | 0.00 | **0.313** | | | |
| **8** | | **avg SPC** | 6.12 | 22.41 | 181.55 | 132.94 | 186 | 166.83 | 0.81 | 0.27 | **0.540** | | | |
| **9** | | **min SPC** | 5.78 | 23.64 | 133.89 | 115.07 | 165.55 | 138.17 | 0.73 | 0.54 | **0.637** | | | |
| **10** | **B1** | **avg 3 SPC** | 6.17 | 21.83 | 160.97 | 127.54 | 179.91 | 156.14 | 0.83 | 0.37 | **0.597** | 0.793 | 0.40 | 0.594 |
| **11** | | **min 3 SPC** | 5.78 | 23.64 | 133.89 | 115.07 | 165.55 | 138.17 | 0.73 | 0.54 | **0.637** | | | |
| **12** | | **EE** | 6.3 | 22.55 | 211.53 | 125.52 | 164.86 | 167.30 | 0.86 | 0.26 | **0.559** | | | |
| **13** | | **avg SPC** | 4.91 | 24.11 | 139.76 | 187.01 | 135.75 | 154.17 | 0.53 | 0.39 | **0.457** | | | |
| **14** | | **min SPC** | 4.84 | 23.46 | 136.86 | 174.21 | 129.86 | 146.98 | 0.51 | 0.46 | **0.483** | | | |
| **15** | **B2** | **avg 3 SPC** | 4.99 | 22.93 | 120.18 | 180.95 | 121.84 | 140.99 | 0.55 | 0.51 | **0.530** | 0.523 | 0.44 | 0.480 |
| **16** | | **min 3 SPC** | 4.84 | 23.46 | 136.63 | 174.21 | 129.86 | 146.90 | 0.51 | 0.46 | **0.483** | | | |
| **17** | | **EE** | 4.91 | 23.67 | 151.3 | 187.49 | 130.18 | 156.32 | 0.53 | 0.37 | **0.446** | | | |
| **18** | | **avg SPC** | 5.14 | 23.72 | 154.59 | 157.59 | 137.38 | 149.85 | 0.58 | 0.43 | **0.505** | | | |
| **19** | | **min SPC** | 5.22 | 23.41 | 131.23 | 139.53 | 135.6 | 135.45 | 0.60 | 0.57 | **0.584** | | | |
| **20** | **B3** | **avg 3 SPC** | 5.27 | 22.61 | 111.22 | 145.38 | 122.84 | 126.48 | 0.61 | 0.65 | **0.633** | 0.602 | 0.56 | 0.580 |
| **21** | | **min 3 SPC** | 5.22 | 23.41 | 131.23 | 139.53 | 135.6 | 135.45 | 0.60 | 0.57 | **0.584** | | | |
| **22** | | **EE** | 5.29 | 22.7 | 110.88 | 165.52 | 129.13 | 135.18 | 0.62 | 0.57 | **0.593** | | | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **23** | | **avg SPC** | 4.44 | 28.01 | 94.67 | 96.08 | 140.82 | 110.52 | 0.41 | 0.81 | **0.611** | | | |
| **24** | | **min SPC** | 4.46 | 27.98 | 100.36 | 102.9 | 152.62 | 118.63 | 0.42 | 0.73 | **0.574** | | | |
| **25** | **C1** | **avg 3 SPC** | 4.15 | 30.9 | 95.36 | 99.5 | 154.91 | 116.59 | 0.35 | 0.75 | **0.547** | 0.382 | 0.77 | 0.577 |
| **26** | | **min 3 SPC** | 4.46 | 27.98 | 100.36 | 102.9 | 152.62 | 118.63 | 0.42 | 0.73 | **0.574** | | | |
| **27** | | **EE** | 4.01 | 30.01 | 99.36 | 83.81 | 136.88 | 106.68 | 0.31 | 0.84 | **0.578** | | | |
| **28** | | **avg SPC** | 4.61 | 28.78 | 130.63 | 85.22 | 88.24 | 101.36 | 0.45 | 0.89 | **0.675** | | | |
| **29** | | **min SPC** | 4.67 | 29.41 | 149.16 | 84.49 | 86.55 | 106.73 | 0.47 | 0.84 | **0.656** | | | |
| **30** | **C2** | **avg 3 SPC** | 4.76 | 30.24 | 118.29 | 97.55 | 103.1 | 106.31 | 0.49 | 0.85 | **0.669** | 0.458 | 0.89 | 0.672 |
| **31** | | **min 3 SPC** | 4.67 | 29.41 | 149.16 | 84.49 | 86.55 | 106.73 | 0.47 | 0.84 | **0.656** | | | |
| **32** | | **EE** | 4.41 | 32.66 | 109.75 | 74.85 | 86.7 | 90.43 | 0.41 | 1.00 | **0.704** | | | |
| **33** | | **avg SPC** | 4.65 | 26.8 | 145.37 | 104.31 | 102.14 | 117.27 | 0.46 | 0.74 | **0.603** | | | |
| **34** | | **min SPC** | 4.51 | 27.92 | 155.87 | 104.09 | 99.78 | 119.91 | 0.43 | 0.72 | **0.574** | | | |
| **35** | **C3** | **avg 3 SPC** | 4.53 | 29.5 | 167.46 | 98.35 | 110.28 | 125.36 | 0.44 | 0.66 | **0.550** | 0.432 | 0.71 | 0.569 |
| **36** | | **min 3 SPC** | 4.51 | 27.92 | 155.87 | 104.09 | 99.78 | 119.91 | 0.43 | 0.72 | **0.574** | | | |
| **37** | | **EE** | 4.38 | 28.45 | 158.97 | 105.39 | 104.65 | 123.00 | 0.40 | 0.69 | **0.543** | | | |

**Legend:**

: Best result

: Average result

: Worst result

A brief look at the results in Table 8 shows that random assignment of workers to tasks gives the worst results, as expected. Since the workers' capabilities and task demands are not taken into account during assignment, ineligible workers are assigned to tasks that they are least competent in. This leads to low productivity values, high utilizations, and consequently low performance (0.259).

Assignment technique #2 shows the best results with the highest overall performance value among all techniques (0.824). In this technique, the SPCs of the most affected body part for each task are identified and sorted in ascending order, and the worker with the highest strength in the concerned body part is chosen. In the case where a worker happens to have the highest strength in two different body parts, he is assigned to the more critical task with the lower SPC value.

The rest of the techniques include the proposed scores, and their overall performance, productivity, and safety results vary depending on each score and task demands. Thorough analysis of the results will be performed from two perspectives. The first perspective is the "Scores Aspect", where the average results of the five different task demands for each score (average SPC, minimum SPC, average SPC for the 3 joints, minimum SPC for the 3 joints, and energy expenditure) will be compared with the other average results of the rest of the scores. This perspective will give an insight into the overall potential of each score. The second perspective is the "Task Demands Aspect", which gives an insight into the results of each of the five task demands.

## 6.1 Scores Aspect

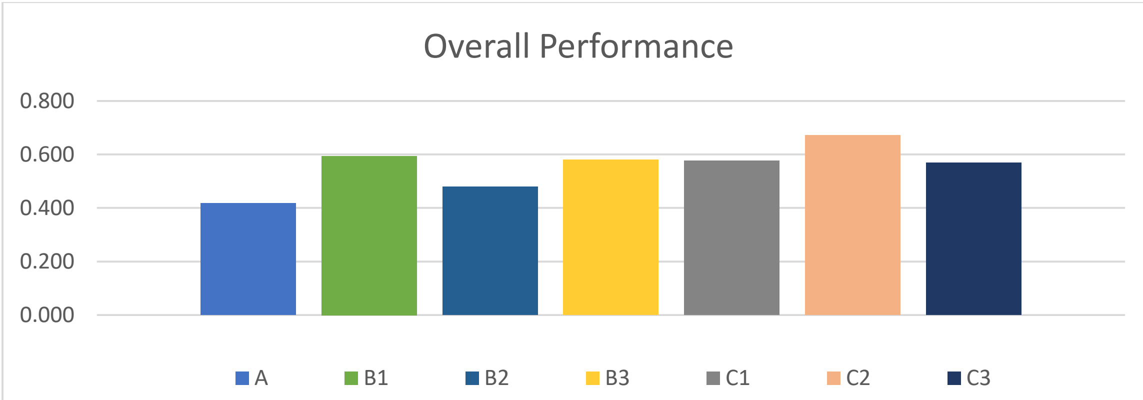


Figure 7 - Overall Performance Results For All Score

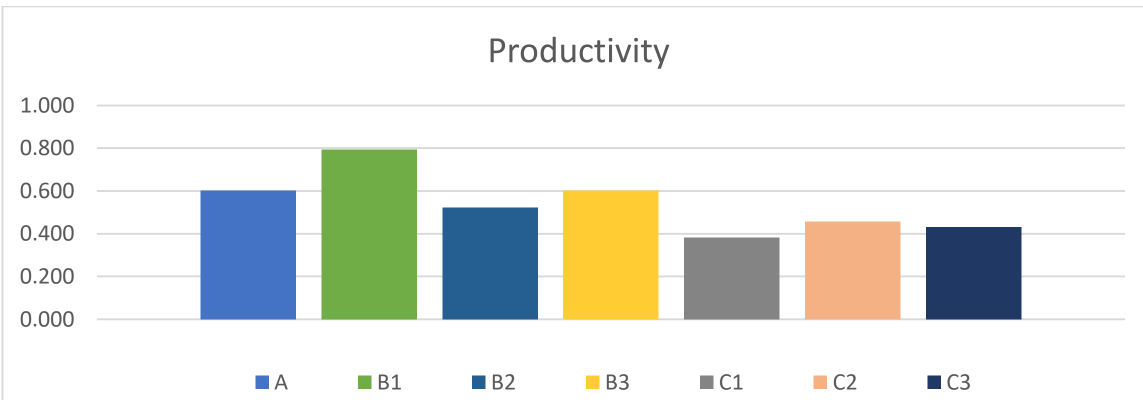


Figure 8 - Productivity Results For All Scores

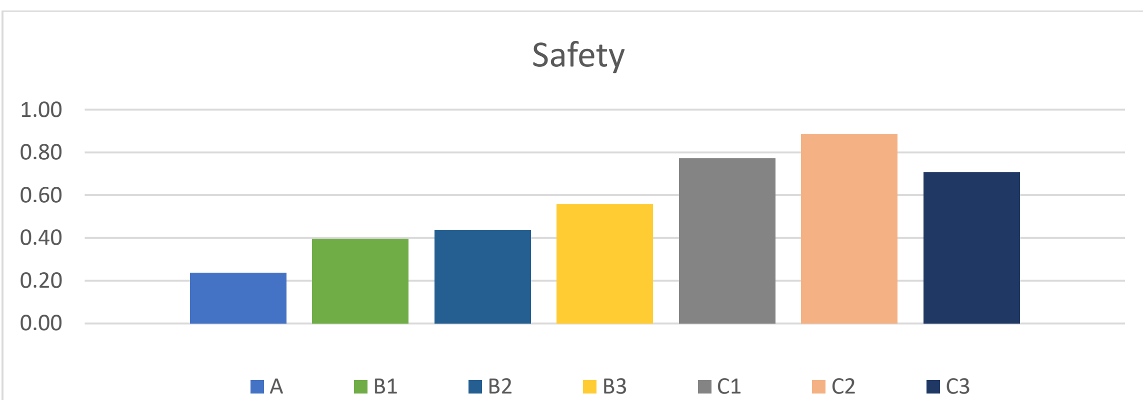


Figure 9 - Safety Results For All Scores

As shown in Figures 7, 8, and 9, in the first category including the techniques where the scores that represent both strength and experience are used such as score A, B1, B2, and B3, the productivity values are relatively high, while safety values are relatively low. In these techniques, the scores give physical strength a weight of 0.5 and experience a weight of 0.5. Since safety in this study is the complement of body part utilization, low safety values represent high body part utilizations. Therefore, these techniques allow the assignment of workers that might not be 100% physically compatible with the tasks, due to taking their experience into account in addition to their physical strength. These techniques can therefore be used in crews where productivity is given higher importance than physical safety.

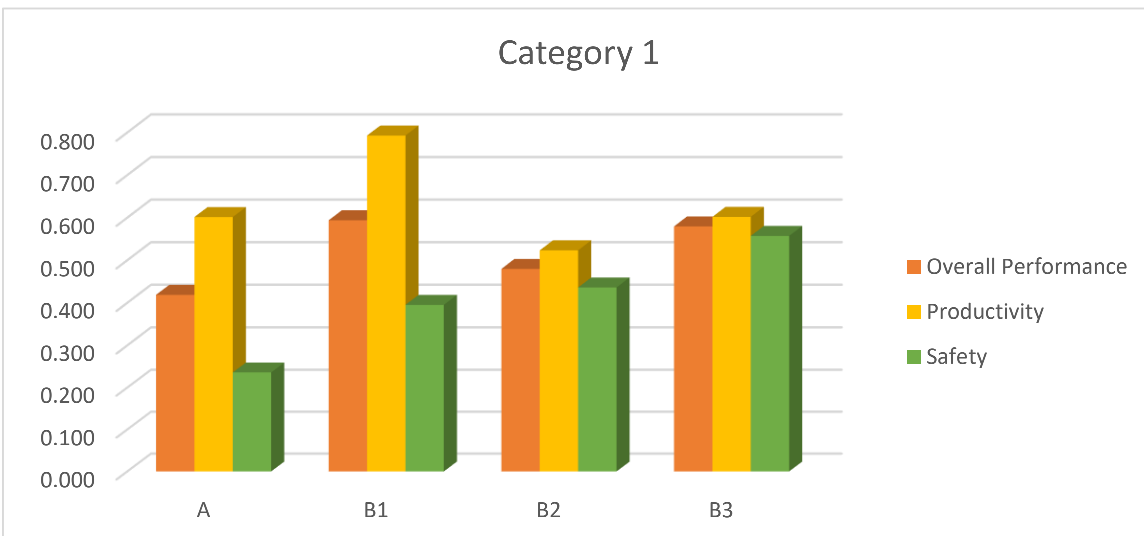


Figure 10 - Category 1 Scores Results

According to Figure 10, in this category, the score with the highest average overall performance value is score B1(0.594), which also gives the highest average productivity value (0.793). Score B1 takes experience, arm strength, back strength, and grip strength into consideration. It is also worth mentioning that score B1 was inspired by the strength index (SI) proposed by (Jackson et al. 1992) which is the sum of the isometric arm, back, and grip test scores.

The score with the lowest average overall performance in this category is score A (0.419) with also the lowest average safety value (0.24). Score A represents both strength and experience, but strength is not the raw strength score obtained from the strength tests. Instead, it is the ratio of the body strength to the required joint torque.

However, in the second category (Figure 11) including the techniques where the scores that represent only strength are used such as scores C1, C2, and C3, the productivity values are relatively low, while safety values are relatively high. Since scores C1, C2, and C3 are a function of physical strength only, then the criterion followed for assigning the workers depends on their physical strengths. Therefore, the workers chosen for each task have enough body strength to perform the tasks, and not much of their body strength is utilized while working. These scores and their corresponding criteria can be used in crews where physical safety is of high importance.

In this category, the results are quite similar, with score C2 having the highest average overall performance value (0.672), the highest average productivity value (0.458), and the highest average safety value (0.89). Score C2 is calculated by adding the knee, arm, and back strengths.

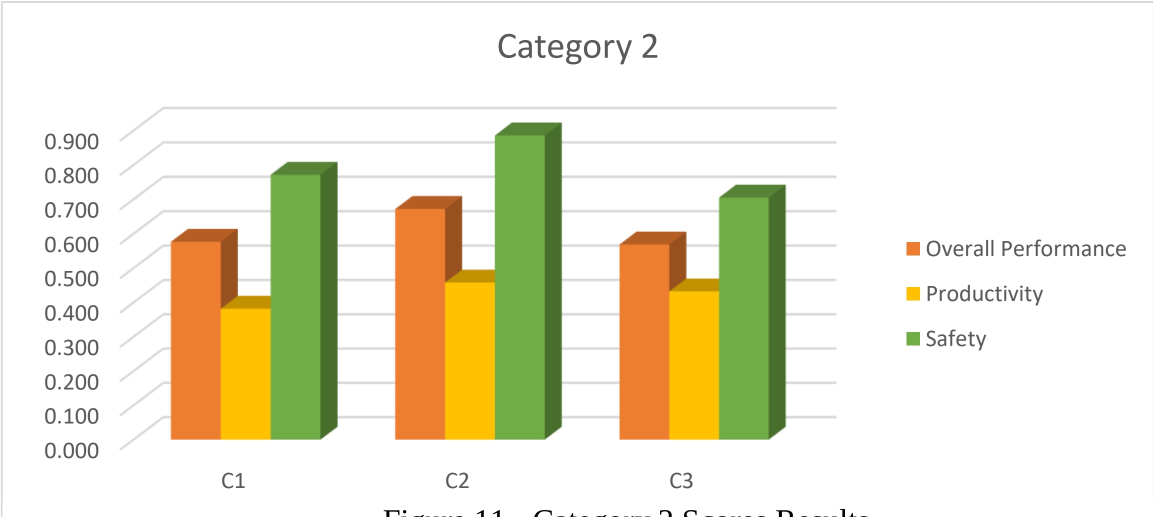


Figure 11 - Category 2 Scores Results

### 6.2 Task Demand Aspect

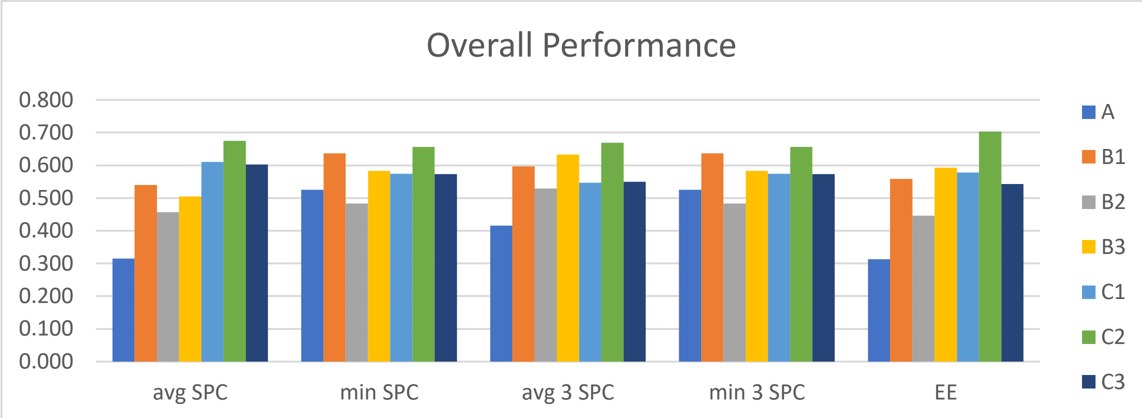


Figure 12 – Task Demands Overall Performance Results

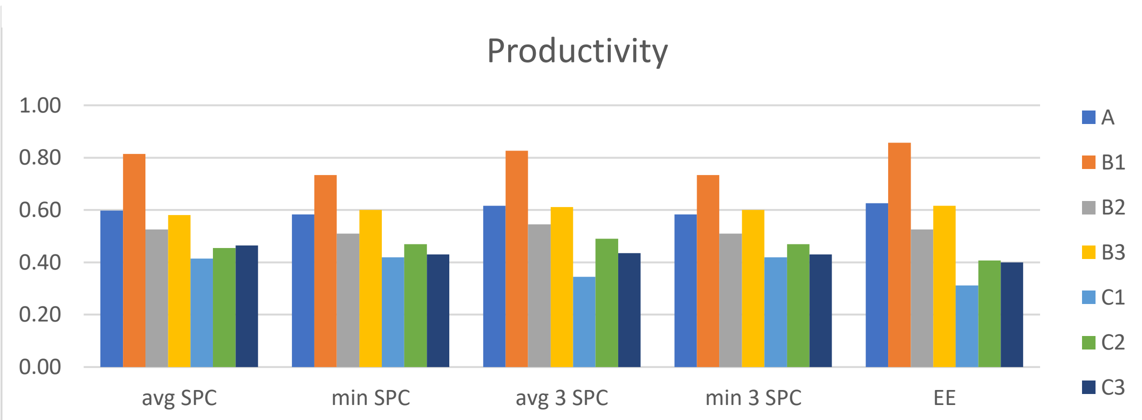


Figure 13 – Task Demands Productivity Results

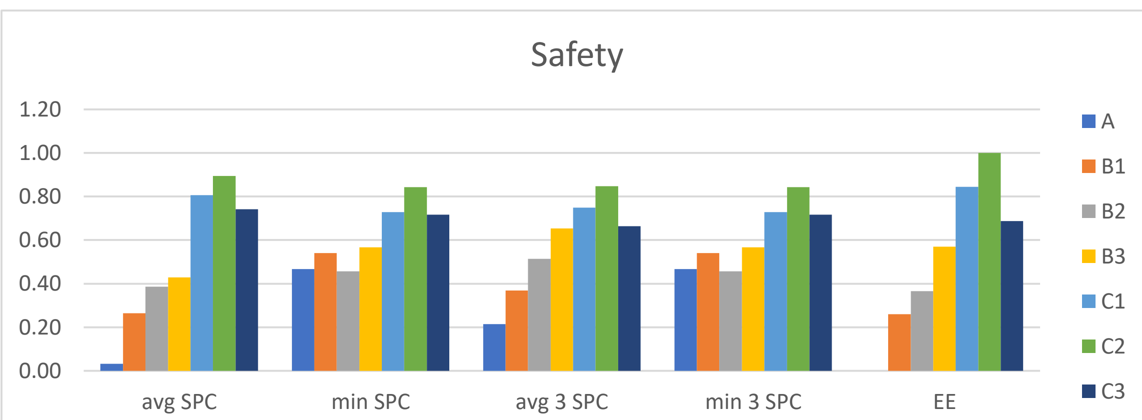


Figure 14 - Task Demands Safety Results

As seen from Figures 12, 13, and 14, no major differences can be noted among the different task demands (average, minimum, energy expenditure, …). The averages of the task demands are close in value.

In the first category, the overall performance values of the assignment techniques where the average SPC of all joints and the energy expenditure are taken into account (blue bars in Figure 15) are generally slightly lower than the rest of the techniques. The same thing applies to the safety values of scores A and B1 (Figure 16). Score B3, however, gives acceptable performance and safety values in the techniques where energy expenditure was used.

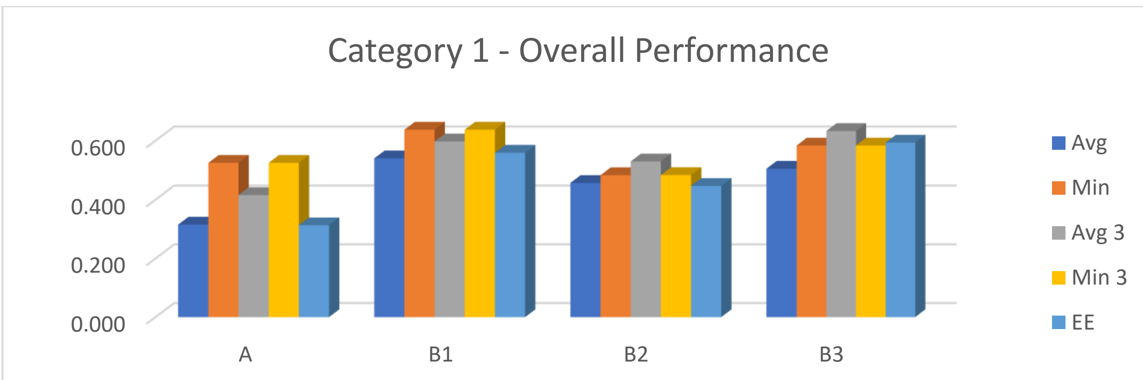


Figure 15 – Task Demands Overall Performance Per Score – Category 1

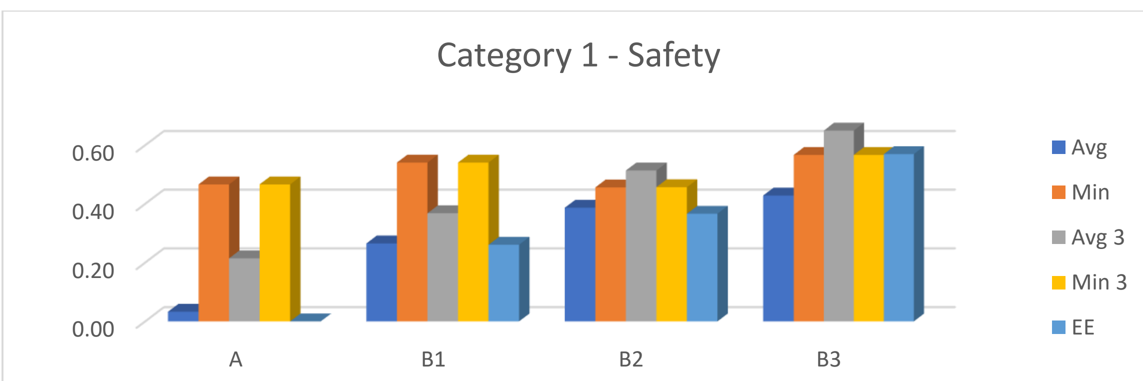


Figure 16 - Task Demands Safety Per Score - Category 1

The productivity values (Figure 17), however, are the opposite. Although the values are extremely close to each other, they are slightly higher in the techniques where the average SPC of all joints, the average SPC of the three most common joints, and the energy expenditure are taken into account. Score B3 gives almost equal values in all cases.

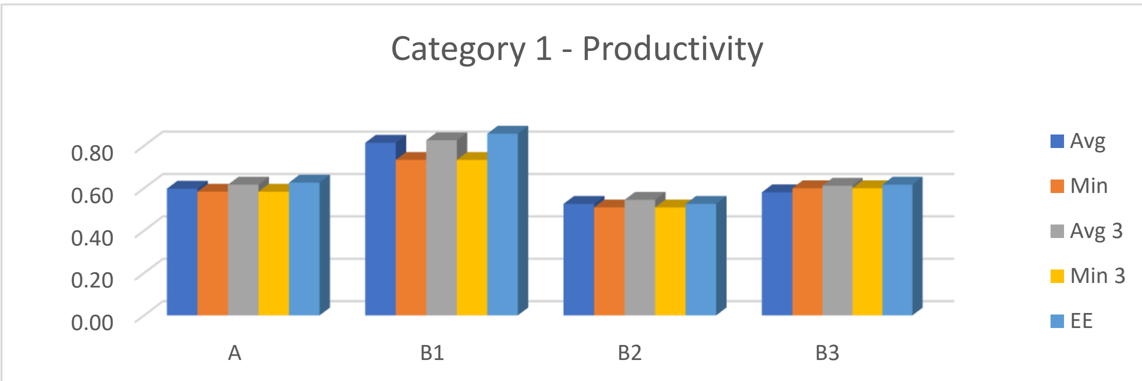


Figure 17 - Task Demands Productivity Per Score - Category 1

A rational explanation to justify the results of the first category would be that when experience is taken into consideration, physical strength is given a weight of 0.5 only. Therefore, focusing on the body part that has the least SPC value ensures the safety of the workers by not utilizing too much of their strength capacity, but it does not ensure fast and productive execution of the scheduled tasks.

In the second category, the results are extremely similar. Generally, the techniques where the average SPC of all joints is taken into account, the overall performance, productivity, and safety values (Figures 18, 19, and 20 respectively) are slightly higher than other techniques.

It is safe to say from the obtained results that the task demands do not have any significant impact on the performance, productivity, or safety of the crews.

In conclusion, different scores resulted in varying outcomes, while task demands did not have a significant impact on the outcomes of the simulation runs.

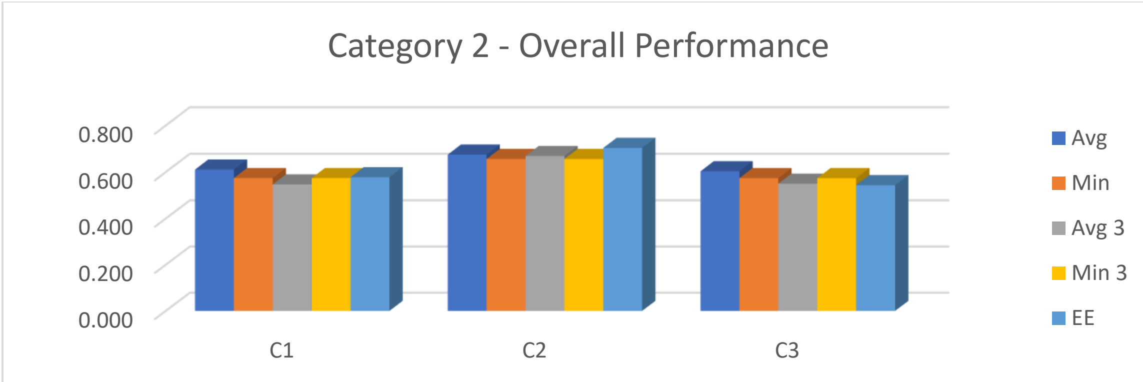


Figure 18 - Task Demands Overall Performance Per Score - Category 2

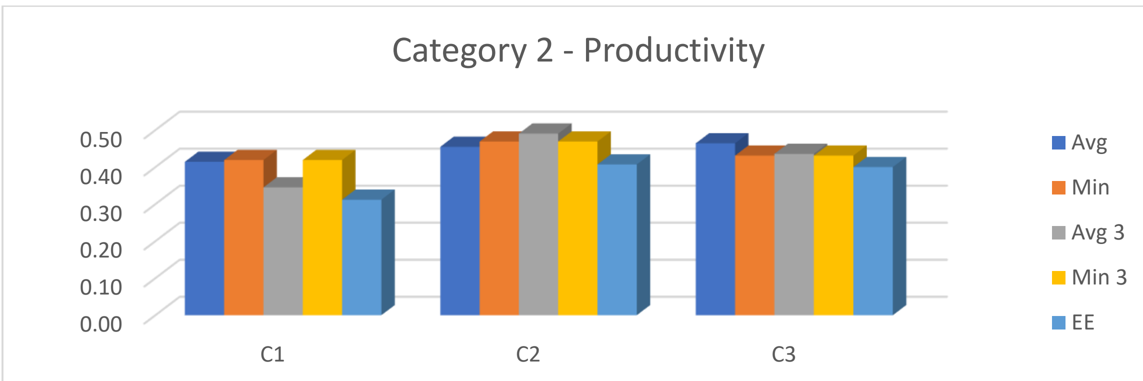


Figure 19 - Task Demands Productivity Per Score - Category 2

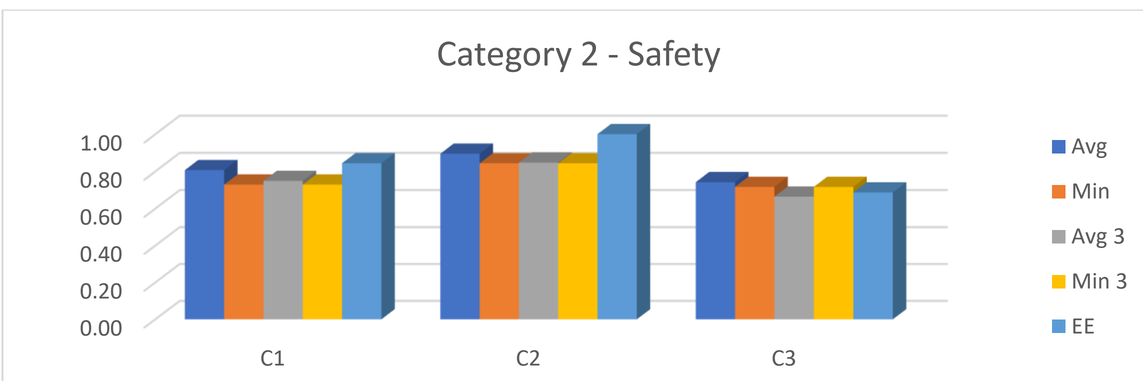


Figure 20 - Task Demands Productivity Per Score - Category 2

## 6.3 Different Weights Assignment

Equation 10 where different weights can be assigned to the results can serve as a means to combine both variables, productivity and safety, together by setting weights for each. It also allows the user to evaluate the crew's performance by favoring one variable over the other.

The same results obtained from the simulation runs were given different weights to study how the overall performance results will vary. In the first case, productivity and safety are given equal weights of 0.5. In the second case, productivity was given a weight of 0.25 and safety was given a weight of 0.75. In the third case, the weights were switched. The results for all cases are shown in Table 10 for comparison.

Table 10 - Overall Performance Results For Different Weights

| Score | A | B1 | B2 | B3 | C1 | C2 | C3 |
|---|---|---|---|---|---|---|---|
| **Equal Weights** | 0.419 | 0.594 | 0.48 | 0.58 | 0.577 | 0.672 | 0.569 |
| **Favoring Safety** | 0.309 | 0.475 | 0.453 | 0.566 | 0.693 | 0.8 | 0.651 |
| **Favoring Productivity** | 0.528 | 0.713 | 0.506 | 0.593 | 0.46 | 0.544 | 0.487 |

As shown in the table, while score C2 had the best performance values in the case where both results are given equal weights and the case where safety is favored, score B1 had the best performance value in case productivity was favored. Contractors can therefore assign different weights based on their preferences and choose the assignment technique that gives the best performance result.

# CHAPTER 7

# VALIDATION SURVEY

A survey was conducted among site engineers from Lebanon. This chapter discusses the different objectives, sections, and results of the survey.

## 7.1 Survey Objectives

The survey was conducted for two purposes. The first purpose is to validate the results obtained from the assignment techniques through ABM. The second purpose is to test the readiness of contractors to use the propose tool as a method for optimizing crew performance through physiological measurements and simulation of different assignment techniques.

## 7.2 Survey Sections

The survey is composed of three sections. In the first section, the respondents specify their position and years of experience. In the second section, they respond to questions addressing the assignment techniques and their expected performance results to validate the ABM results. In the third section, they respond to questions assessing their readiness to implement or suggest implementing the proposed assignment techniques in real projects in the future.

## 7.3 Results Validation

In order to validate the results obtained from the agent-based model, they were asked about their opinion, based on their experience, on each technique.

First, each assignment technique was explained, and they were asked to rate the expected performance of a construction crew where each technique was used. From their experience with worker allocation, site engineers were able to confirm whether the results do reflect realistic outcomes or not.

Since site engineers are generally not knowledgeable about ergonomic and physiological aspects such as energy expenditure or strength percent capable, the questions were general and did not address detailed terms or results.

### 7.4 Tool Practicality

After answering the questions regarding the validation of the ABM results, site engineers evaluated the practicality of the tool and their readiness to utilize it in future projects. The questions addressed the respondents' satisfaction regarding their crews' performance, the frequency of complaints about injuries, the commonly followed assignment techniques, and three questions about the possibility of considering the usage of the proposed tool.

### 7.5 Survey Results

26 responses were received, and the answers varied from one to another. 67.7% of the respondents are construction site engineers, 19.4% are construction managers, and the rest are architects or structural engineers. (Figure 21).

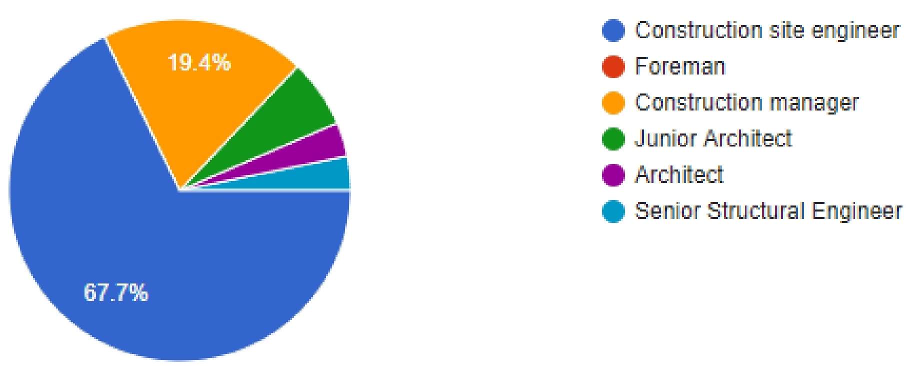


Figure 21 - Respondents' Positions

65.4% of the respondents have between 1 to 5 years of experience, 23.1% have 5 to 10 years of experience, while 11.5% have more than 10 years of experience (Figure 22).

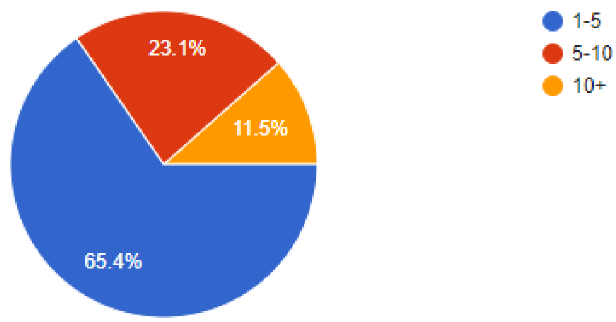


Figure 22 - Respondents' Years of Experience

In the first part of the survey, when asked about their opinion on crews where workers are randomly assigned to tasks, 53.8% of the respondents thought their performance would be the worst, 38.5% thought it would be bad, and 7.7% thought it would be normal (Figure 23).

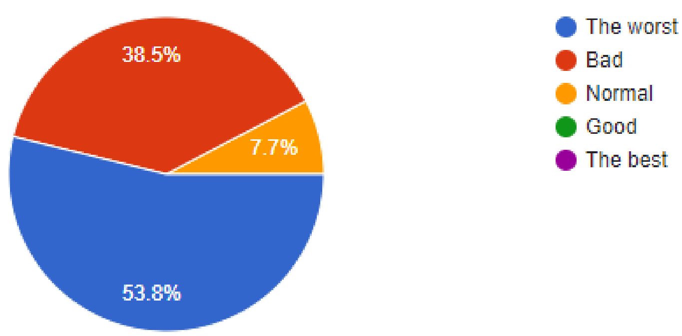


Figure 23 - Random Assignment Answers

The actual performance according to the simulation runs was in fact the worst. When asked about their opinion on crews where workers are assigned to tasks based on their strongest body part (Example: the worker with the strongest arms is assigned to the task that requires the highest arm strength), 50% thought their performance would be the best, 46.2% thought it would be good, and 3.8% thought it would be normal (Figure 24).

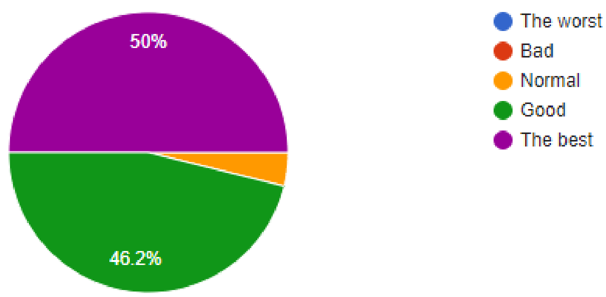


Figure 24 - Strongest Body Part Assignment Answers

Based on the simulation runs, this scenario yielded the best performance results. Finally, when asked about the most accurate assignment technique in their opinion, 88.5% thought that the assignment should be based on the worker's experience and physical strength by comparing his strength to the task demands, while 11.5% thought it should be based on the worker's experience and physical strength, independent of the task demands (Figure 25). According to this study, assigning workers based on their experiences and physical strengths by comparing their strength to the task demands (Score A) was not the best technique. Instead, the best performance value was obtained from the techniques where score C2 was used. Score C2 is calculated by averaging the knee, arm, and back strengths of each worker.

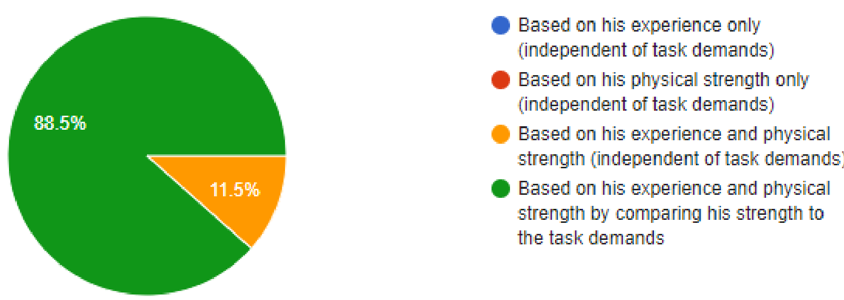


Figure 25 - Most Accurate Assignment Technique Answers

In the second part, respondents were asked some questions regarding the practicality of the purpose tool. The first question addressed the assignment technique commonly followed in their projects. 84.6% said that each worker is assigned to the task he is most experienced in, while 15.4% said that workers are assigned randomly to tasks (Figure 26).

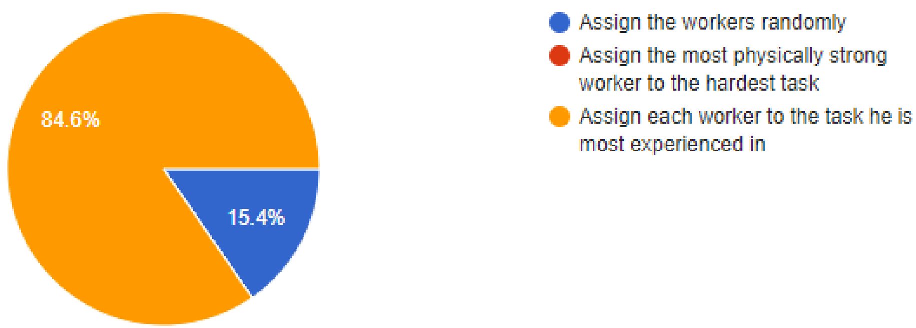


Figure 26 - Assignment Techniques

When asked about their satisfaction regarding their crews' performances, 46.2% were neutral, 38.5% were dissatisfied, while 15.4% were satisfied (Figure 27).

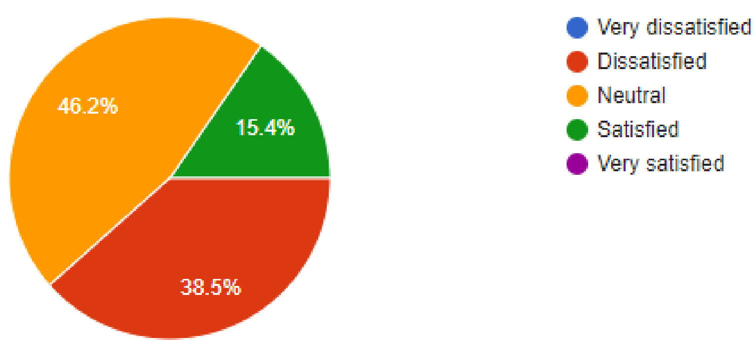


Figure 27 - Performance Satisfaction

Moreover, 57.7% of the respondents said that workers sometimes complain about physical injuries or discomfort, while 34.6% said that this always occurs (Figure 28).

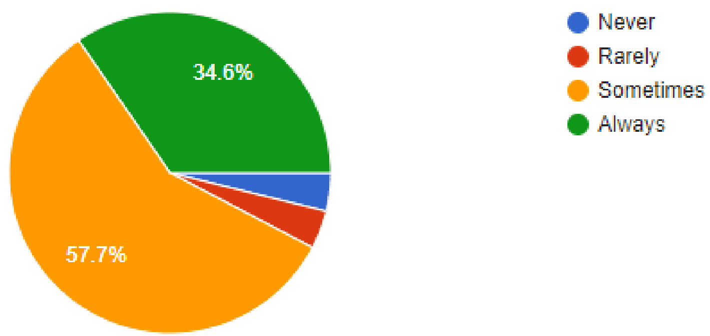


Figure 28 - Physical Injuries and Discomfort Complaints Frequency

80.8% thought that construction crews would absolutely agree on measuring their physical strengths only once to improve their performance (Figure 29).

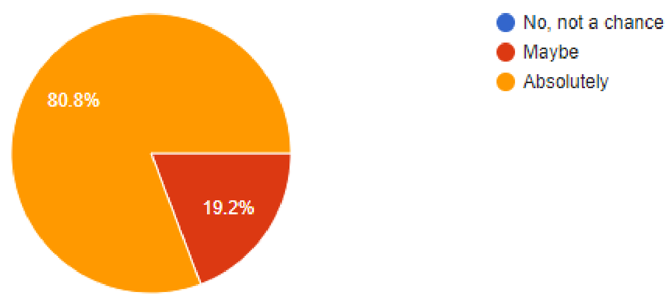


Figure 29 -Workers' Readiness To Measure Strengths

88.5% said that they would absolutely consider implementing a technique where physical strengths of workers are measured only once and inserted into a tool that calculates their possible performances under different assignment techniques (Figure 30).

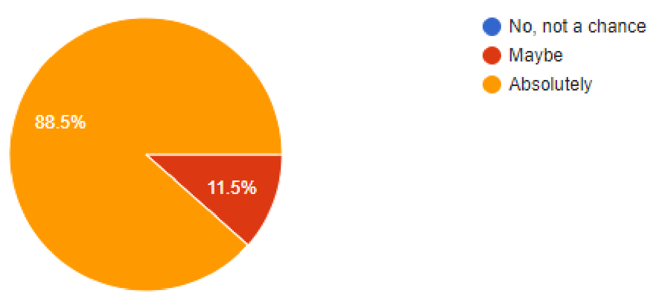


Figure 30 - Respondents' Readiness To Implement The Framework

Finally, 88.5% thought that this proposed technique is practical can be easily implemented (Figure 31). The survey results show that contractors are open to implementing the proposed techniques.

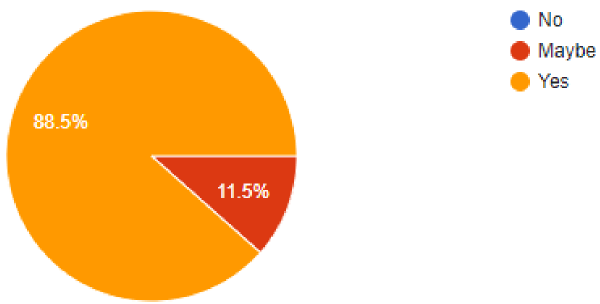


Figure 31 - Tool Practicality Responses

# CHAPTER 8

# CONCLUSION

## 8.1 Summary

In the topic of construction task assignment, several studies were conducted in an attempt to optimize the performance of construction crews. Some studies have measured physiological capabilities, while other studies have linked the mental workload with the workers' mental capabilities. However, no study has yet been conducted to estimate physiological workload and match it with its corresponding physiological capabilities of the workers. Therefore, this research will address the physiological side of the task demands and applied capabilities.

This study proposes the usage of DHM and ABM for proactive performance control of construction crews by studying different assignment techniques. DHM allows the modelling of different construction tasks to obtain task demands, and ABM allows the modelling of the assignment of workers to tasks to obtain performance values in terms of productivity and safety. Different techniques are modelled and compared. From this study's simulation results, and in the case of giving the productivity and safety a weight of 0.5 each, score C2 resulted in the highest overall performance and safety values, while score B1 resulted in the highest productivity value. Assignments based on different task demands, however, did not affect the outcome significantly.

Although the workers' data in this study are assumed, contractors, project stakeholders, managers, or foremen with real workers' measured data have the option to choose their weights for each of the productivity and safety in order to select their preferred assignment technique. Such a framework can help improve project performance by taking appropriate task assignment into account. This method was assessed through a survey among site engineers to evaluate its practicality and feasibility.

## 8.2 Possible Practical Implementation in Future Projects

As the aim of this research is to enhance the performance of construction crews in terms of productivity and safety through appropriate worker allocation, contractors may employ the proposed tool to assist in deciding on the best assignment technique to be followed. In order to be able to make use of the tool, several steps should be followed.

### *8.2.1 Physiological Measurements*

Several strength tests are available for measuring muscle strength, and contractors may use them to measure their workers' capabilities as a first step in the procedure. Isometric devices have been used for years to measure muscle strengths (Townsend et al. 2010), and the first strength test to be performed by the contractors is the handgrip strength test which is the most commonly performed test (Kolimechkov et al. 2020). Handgrip strengths can be measured using different dynamometers, such as TKK digital dynamometer and DynX electronic dynamometer. The worker should be seated, and the grip dynamometer is held with the palm facing upwards (Xiao et al. 2005). The other strength tests are the arm lift test, back (torso) lift test, and leg lift test (Feeler et al. 2010). There are several methods so measure each strength. For example, the arm lift test is used to measure arm strength by exerting some force by lifting with the arms at a 90-degree flexion angle with the elbows (Xiao et al. 2005). The leg lift test is used to measure lower extremity endurance (Haghigh et al. 2019) by standing with their feet shoulder-width apart and exerting an upward lifting force with the dynamometer placed between the workers' knees. In the back or torso lift test, the workers stand with their legs in a straight line with the upward vertical force where they exert an upward lifting force (Townsend et al. 2010).

By performing the mentioned tests, the body part strengths of the workers can be measured and recorded as a physiological database for the crew.

#### *8.2.2 Data Import into The Agent-Based Model*

Physiological data of the workers along with their experience levels, and learning rates are imported into the agent-based model as crew data. The tasks schedule for the first week are then inserted with their corresponding task demands, average durations, and required number of workers. Task demand data may be obtained either from the already modelled and simulated tasks in this study, or from newly modelled and simulated tasks using any DHM software.

#### *8.2.3 Simulation Runs*

Once crew and task data are inserted into the model, several runs can be performed, each representing a single assignment technique. Different combinations of scores and task demand criteria may be tested, and productivity and body part utilization values – which represent safety - are obtained for each technique. All results are recorded for analysis.

#### *8.2.4 Technique Selection*

Once the results are obtained, the contractors may assign a weight for each result. For example, a contractor who favors safety over productivity may give safety a weight of 0.7 and productivity a weight of 0.3. The final performance value is obtained, and the contractor can select the assignment technique that yields the best performance.

### 8.3 Limitations and Future Work

While the proposed study has achieved significant results by studying and analyzing different assignment techniques, it exhibits some limitations. The base of the study which is the task demands was obtained from the DHM software Jack. These task demands were inserted into the agent-based model and are the engine for assigning workers, but they were not verified or validated. Some results such as the energy expenditure of some tasks were verified by comparing them to the results of other research studies, as already mentioned in the previous chapters. However, for reliability, the results from Jack should be verified by actual construction workers who perform the tasks and are physically affected by the task demands through discomfort, fatigue, or even injuries. This will be part of the future works that must be completed to be able to improve the reliability and credibility of the study. Another limitation is the assumptions made to build the agent-based model. For example, the “Knowledge Sharing” or “Transferred Experienced” was inserted into the model as an increase of experience by 10% whenever a worker performs a task with a more experienced worker. This increase must be tested and validated for more accurate results. Furthermore, although learning and experience were taken into account in this study, more psychological aspects of workers can be incorporated for an accurate representation of labor productivity and performance in construction crews. Such aspects could include leadership behavior which affects the morale of the workers, trust among the crew which could affect knowledge sharing, and so on. Future works also include expanding the list of modelled construction tasks to cover as many tasks as possible. A database of all modelled tasks and their measured and validated task demands can then be created and utilized for all construction projects. Moreover, the different assignment techniques can be tested on different construction crews of different physiological capabilities instead of just one crew. This would provide a more accurate measure of the effectiveness of each assignment technique and the proposed framework in general. Finally, more techniques and scores can be proposed and tested for a wide variety of assignment technique options to be used by contractors.

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# APPENDIX A

# SURVEY QUESTIONNAIRE

CONSTRUCTION ASSIGNMENT TECHNIQUES SURVEY

*This survey is made for research purposes as part of a master's thesis at the American University of Beirut (AUB) about the importance of matching physiological capabilities of construction workers to task demands during task assignment.*

*The survey should take 10 minutes to complete. All answers will be confidential.*

**Introduction**

This survey is twofold.

The first part is directed towards validating performance results obtained from the study.

The second part is directed towards studying the readiness of contractors to use the proposed tool for task assignment.

1. What is your current position?
   A. Construction site engineer
   B. Foreman
   C. Construction manager
   D. Other:
2. How many years of experience do you have?
   A. 1-5
   B. 5-10
   C. 10+

**Part 1: Results Validation**

*Please answer the following questions based on your experience.*

3. In a crew where workers are RANDOMLY (without any specific criteria) assigned to tasks, how would their performance (productivity and physical safety) be?
   A. The worst
   B. Bad
   C. Normal

D. Good
E. The best

4. In a crew where workers are assigned to tasks based on their strongest body part (Example: the worker with the strongest arms is assigned to the task that requires the highest arm strength), how would their performance (productivity and physical safety) be?
   A. The worst
   B. Bad
   C. Normal
   D. Good
   E. The best
5. Which method of assessment do you think is the most accurate for evaluating the eligibility of a construction worker to perform a task? (Task demand = the required physical strengths)
   A. Based on his experience only (independent of task demands)
   B. Based on his physical strength only (independent of task demands)
   C. Based on his experience and physical strength (independent of task demands)
   D. Based on his experience and physical strength by comparing his strength to the task demands

**Part 2: Task Assignment Tool**

6. What are the assignment techniques usually followed in the projects you work on?
   A. Assign the workers randomly
   B. Assign the most physically strong worker to the hardest task
   C. Assign each worker to the task he is most experienced in
   D. Other:
7. How satisfied are you with the performance of the construction crews in the projects you work on?
   A. Very dissatisfied
   B. Dissatisfied
   C. Neutral
   D. Satisfied
   E. Very satisfied

8. How often do workers in the projects you work on complain about physical injuries/discomfort?
   A. Never
   B. Rarely
   C. Sometimes
   D. Always
9. Do you think construction crews would agree on measuring their physical strengths only once to improve their performance?
   A. No, not a chance
   B. Maybe
   C. Absolutely
10. Would you consider implementing a technique where physical strengths of workers are measured only once and inserted into a tool that calculates their possible performances under different assignment techniques?
    A. No, not a chance
    B. Maybe
    C. Absolutely
11. Do you think the proposed technique is practical and can be easily implemented?
    A. No
    B. Maybe
    C. Yes