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Research article

Developing a novel energy-based approach for measuring mental workload

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ABSTRACT

Minimal research has been conducted to develop non-invasive processes for quantifying and evaluating worker mental workload - a critical concern - at the task level in the construction industry. One reason for this gap in research is the complex and dynamic nature of the construction process, which makes construction work more complicated to measure and predict compared to work in other industries. This paper presents a novel approach and corresponding conceptual model to quantify and evaluate construction worker perception of mental workload at the task level using the energy concept. A conceptual process for assessing mental workload (MWL), i.e., the feeling of stress, pressure, and being overwhelmed due to the task nature, factors, conditions, and resources that accompany the performance of the task, was developed from extant research and interviews. The Delphi method was utilized to characterize the energy-based model and provide initial verification. The results from the literature review, expert insight, and four rounds of the Delphi survey revealed 14 constituents, 51 components, and one metric for each component to measure the level of MWL felt by a worker. These constituents, components, and metrics were used to develop a model for measuring construction worker MWL. This study contributes to knowledge by developing a novel non-invasive method for assessing potential task-level MWL using an energy-based model. The energy-based assessment model contributes to practice by providing a tool that could be used to measure the potential impact of construction tasks on workers perceived mental workload.

1. Introduction

Given the construction industry's dynamic, fragmented, and complex nature and its work processes, holistic performance improvement can be challenging [1]. Unlike the manufacturing industry, the construction industry largely relies on construction workers, human interaction, and involvement in work processes and operations [2,3]. Unfortunately, people, by nature, are error-prone [4], and this innate limitation can lead to significant negative consequences for worker performance. Moreover, when this limitation is combined with the demanding and high-risk work environment typical of most construction projects, the probability of a successful outcome reduces significantly. Due to individual worker characteristics and project uniqueness, human error frequency is likely unevenly distributed among individual workers, tasks, and projects. Several studies have highlighted factors, such as task

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complexity, distraction, repetition, resource availability, and work pace, that can severely impair worker performance on construction projects [2,5–7]. Working under pressure has become a routine phenomenon in the construction industry, and pressure can negatively affect worker performance [8]. As a result, workers might feel stressed due to production pressure by management to finish a task (e.g., being pressed to work faster), negatively impacting worker performance with respect to certain performance criteria, such as safety [9–11]. Similarly, a worker's unusual, negative, and distracting stress increases their susceptibility to accidents and low-quality behavior [12,13]. In other words, stress distracts a worker's attention and can lead to increased probability of injury.

Available literature captures recommendations on how workers can be safer and more productive at executing tasks when faced with these factors [14–16]. For instance, some studies suggest that identifying and mitigating the critical factors that influence worker mental workload (MWL) reduces the odds of a negative outcome such as poor worker performance [17,18]. MWL is a measure of the amount of mental effort that an individual requires to complete a task in relation to the overall amount of mental energy they have available and cognitive demand they experience [19]. The majority of research conducted thus far has employed cognitive demand to define MWL, and the idea of MWL is frequently addressed in the domains of ergonomics and cognitive psychology, which are concerned with worker performance and potential operational error rates [20,21]. The link between user cognitive task demands and MWL has been studied in the context of occupational safety and transportation, for instance, by Recarte and Nunes 2003 [22] and Zacharatos et al., 2005 [23]. Researchers have also explored the role of stressors on worker performance using multiple constructs [24,25], and highlighted the important role of mental energy to a healthy lifestyle and improved quality of life [26].

Although alertness and fatigue have been studied as possible factors that could affect mental energy [27], there is currently quite limited scientific literature describing the concept of mental energy applied in the present context [26], including as it relates to mental workload. Scientists usually use the term energy to refer to the amount of physical energy that a person has to measure physical work as an energy output [27]. Various studies have been conducted to assess the amount of mental energy using self-report questionnaires, including the Profile of Mood States (POMS) that people experience [28–30]. Although the term mental energy can be used to describe a person's state or mood, it can also be regarded as their ability to perform mental tasks [27]. As mentioned previously, MWL is synonymous with and represents cognitive demand, workload demand, and mental energy. The current study emphasizes the concept of energy as a way to measure MWL levels on construction sites to assess work operations for safety and quality performance. Therefore, for the present study, energy is used as an indicator and a measure of MWL rather than a person's ability to perform mentally (mental energy).

1.1. *Point of departure and research objectives*

Numerous measures have been created to assess mental states [31], including a variety of measures that can be used to identify the effects of pressure on an individual's activity level. The use of subjective judgment to gauge construction worker MWL has been the topic of several research studies. The NASA Task Load Index (NASA-TLX), utilized in construction management research, is one subjective evaluation method. The NASA-TLX is a tool for calculating and rating MWL in a subjective manner based on worker perspectives. It is used to determine a person's MWL while they are working on a job. Performance is evaluated across six dimensions (mental demand, physical demand, temporal demand, effort, performance, and level of frustration) in order to obtain an overall workload rating. Although the NASAT-LX has become extensive use, problems still need to be resolved in terms of MWL assessment [32]. The Fatigue Assessment Scale for Construction Workers (FASCW) is another subjective evaluation tool. Employees in the commercial construction industry can self-report their level of physical and mental fatigue using the FASCW survey instrument. Likewise, the Subjective Workload Assessment Technique (SWAT), which measures subjective workload, is utilized to capture the multidimensional aspect of MWL. SWAT employs a workload assessment approach in which workers are asked to rate the time, mental effort, and emotional stress needs of an activity. Other similar techniques have been developed by psychologists and scientists to assess MWL while subjects conduct activities. However, despite the availability of methods that can be used to assess the MWL of construction workers, a valid method that utilizes subjective measurements of task-related factors remains to be developed.

Considering the human-centric nature of the construction industry, it is important to understand how the relationship between a range of task characteristics and a worker's mental state impacts the worker's perception of the MWL they experience. However, most studies measure performance from an organizational perspective and, in most cases, are based on lagging indicators [33], assess MWL as a static construct (ignores the dynamic relationship between activities and MWL [21], utilize invasive and non-practical methods for assessing MWL on jobsites [34,35], deploy assessment tools that lack construction context [36,37], have limited application across multiple tasks in the construction industry, and ignores the dynamic interactions between task characteristics [38]. The lack of proactive tools that can assess projects on a micro (task or individual) level presents a critical gap in construction project management practices. Dai et al. [2] highlighted the need for researchers to develop proactive methods for assessing MWL and worker performance. In line with the recommendation of Dai et al. [2], Nnaji and Gambatese [39] emphasize the need for tools that assess the impacts of task-related factors, resources, and site conditions on MWL and worker performance criteria.

Measuring and predicting worker perceived workload is a complicated endeavor, especially in complex and dynamic work environments. Given that task and project-related factors impact worker emotions and performance, the researchers posit that a work-energy theory provides a useful lens to better understand the connection between task characteristics, resources, ability to perform tasks, and worker behavior and performance. Developing management solutions based on properties and phenomena within physical sciences is not new. Previous studies have successfully utilized physical attributes as a theoretical foundation for conceptualizing human-related interventions in several disciplines, including construction. For example, Hallowell and Gambatese [40] utilized Newton's third law of motion as a foundation to develop and estimate the amount of safety intervention required for a given level of safety risk. Similarly, Eseonu and Wyrick [41] developed a model for supporting organizational policy decision-making based on the principles of heat transfer. Researchers are now exploring the feasibility of using energy as a framework for developing a new method for predicting and controlling safety and quality performance in the construction industry [33,40–42]. The present study proposes to close the highlighted research gap using the concept and physical characteristics of energy and its derivatives.

The primary goal of the study was to develop an initial novel idea and corresponding conceptual model using “energy” to evaluate MWL. Achieving this goal will enable supervisors, project managers, and frontline workers to assess potential MWL at the work face. To achieve the research goal, three primary objectives were established: (1) conceptualize the energy-based MWL assessment model, (2) develop a process for assessing MWL using the proposed model, and (3) verify the potential utility of the conceptualized assessment model. As noted above, in the context of the energy model developed, the energy quantified is referred to as “mental energy” and conceptualized as an indicator of MWL.

2. Materials and methods

The present study adopted a multi-phased research approach that includes a detailed review of relevant grey and academic articles, expert interviews, and a Delphi study to achieve the central goal of the study. The research process is explained below and depicted in Fig. 1.

2.1. Literature review

The energy-based assessment model for assessing ME felt by a worker was conceptualized following a detailed literature review of articles, reports, and other types of documents from various sources that house relevant studies. Using a keyword search, the research team probed databases, including Scopus, Web of Science, and Google Scholar, to identify relevant literature supporting the present study. This search was supplemented by searching specific relevant databases such as those put forth by the American Society of Civil Engineering (ASCE), Science Direct, Research Direct, Construction Safety Management, American Society of Quality, Construction Industry Institute, and Project Management Institute. Literature related to safety, quality, psychology, human factors, and personnel management topics was located and reviewed to identify task-based constituents that impact ME, components for each constituent, and a metric for each component. The following definitions guided the identification of components, constituents, and metrics.

- *Constituents:* Conditions of the work operation, work environment, and worker experience that impacts the level of ME felt by the worker.
- *Components:* Performance criteria, actions, or plans that can be used to assess a constituent. One or more components may be used to assess each constituent.
- *Metrics:* Measurement units and scales for assessing the extent to which components (performance criteria, actions, or plans) are implemented and present at the workface.

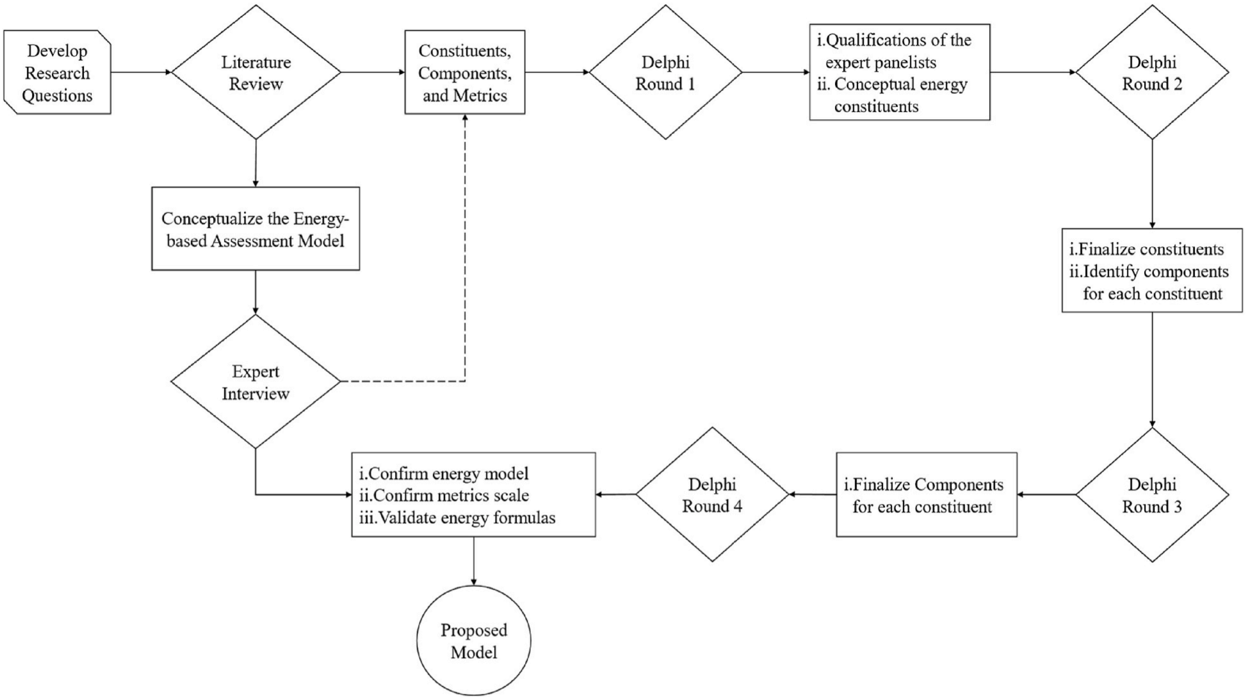

Fig. 1. Research Flow and data collection.

Fifty-four papers were reviewed by the research team related to the research topic. Pertinent papers were carefully evaluated, and thematic coding was applied to delimit the identified factors into feasible categories. Next, influenced by the energy concept, the research team developed an energy-based conceptual model for assessing MWL.

2.2. *Expert interview*

As described above, the conceptual model consists of energy constituents and components discretized into potential and kinetic energy. Discussions with selected construction researchers knowledgeable about safety and worker performance followed this step to verify the rationale behind the energy model. The energy model was presented to 10 construction and occupational safety researchers at two meetings to obtain their input on the model. The review team consisted of assistant, associate, and full professors from five different universities in the US. The researchers who participated in the meetings have over 200 years of construction and occupational health experience across the group. As a result of the discussions with the researchers who participated, the research team adjusted the components and constituents as needed. The review team verified that the list of constituents was representative of the task-related factors that affect MWL, and provided some recommendations related to the constituents and components. For instance, the experts recommended adding “coordination” as a constituent and “Quality of materials, tools, and equipment” as a component within “Availability of needed resources.”

2.3. *Delphi study*

Following the initial assessment by the domain experts, the researchers conducted a Delphi survey to assess the utility of the proposed energy-based model and its constituents and components. The Delphi technique is an interactive, structured, and systematic data-collection process, that relies on a select group of experts to obtain information and knowledge on a specific topic [43]. The Delphi method was selected over other types of research methods (e.g., human subject experimentation) given the exploratory nature of the study, and the need to objectify subjective data. As a fundamental and conceptual-driven study in need of initial verification and validation, it is essential to receive structured feedback from a community of expert [44]. The advantage of using the Delphi method, a recognized scientific method, is that it gathers qualitative data from panelists with diverse backgrounds and areas of expertise to utilize their knowledge and opinions to develop the initial model structure. The Delphi method is also a powerful tool that can be utilized to create new informed and robust models/ideas. Moreover, the Delphi process was selected to help minimize bias compared to other survey methods [45]. The Delphi process includes controls to limit the impact of biases such as the recency effect, von Restorff effect, and neglect of probability [46]. The present study utilized six bias controls to maximize the quality of the research outputs: (1) random selection of expert panelists; (2) removal of panel members who are found not to be qualified as an expert; (3) controlled feedback; (4) multiple rounds of surveys; (5) constituent and component ratings; and (6) reporting median values. For brevity, a detailed description of each control is provided in Refs. [43,46]. The Delphi process typically includes two to six rounds of surveys to achieve consensus amongst expert panelists [47,48]. The group of expert panelists plays a substantial role in the Delphi process. Therefore, the selection of its members is crucial to the success of the process and included as a consideration in its selection as a research method.

2.3.1. *Survey design*

Multiple surveys were designed and distributed in accordance with the Delphi process. The researchers developed a survey for each of the four rounds of the process. Prior to dissemination of the surveys, the researchers obtained Internal Review Board (IRB) approval from Oregon State University for research involving human subjects. Subsequently, an explanation of the research and the first round of the surveys were sent via email to the panel members. The questions for all rounds of the survey were designed using a Likert scale for the answers to ensure the responses were sufficient to determine panelist expertise and arrive at a consensus when rating each constituent and component. The four questionnaires were used to obtain insight from the expert panel needed to (1) verify the conceptualized model and quantify the impact of the existing energy constituents on MWL, (2) finalize the list of constituents and identify components for each constituent, (3) finalize the components for each constituent, and (4) confirm the energy quantification and energy assessment model.

2.3.2. *Expert panel selection*

When using the Delphi method for the present study topic, the individuals who make up the expert panel must have prerequisite knowledge about task-related work impacts to workers to achieve the goals and objectives of the study [46]. Two groups of people were targeted for participation on the expert panel (1) academics (e.g., university professors): and (2) construction industry professionals (e.g., project managers and safety engineers). The selection of potential expert panelists was divided into two steps. The first step to determine members of the panel was to solicit the consent of potential panelists to participate in the research study. An initial list of potential panelists in the academic and industrial fields was created based on the researchers’ personal contact lists, authorship of journal and conference papers related to the research topic, and contacts listed on websites related to the research topic. The next step to determine the panel of experts was an analysis of their experience and knowledge in different areas related to the study topic, such as safety, quality, psychology, human factors, personnel management, worker performance assessment, or a similar field.

Based on the established criteria, the initial list for both occupational fields contained 79 potential expert panelists (19 academics and 60 industry professionals). The researchers randomly selected and invited 60 expert panelists from both academia and industry to participate. The research team contacted, via email, each of the 60 people to invite them to participate in the study. Out of the 60 potential experts contacted, 16 (14 from industry and two from academia) agreed to participate in the study. An expert panel size of

8–18 members is recommended to optimize the Delphi process [46]. Some recent studies utilized between 13 and 17 panelists [49–51]. The 16 panel members have different job titles, including project manager, safety engineer, and faculty member. Also, the 16 experts are involved in various types of organizations, including owner organizations, construction firms, design-build firms, and universities. The average number of years that the panelists have worked in positions related to the study topic is 18 years. To verify the "expert" status of panel members, it is important to qualify each member using a valid assessment method. The success of the Delphi method depends on the qualified and selected panel members and their level of expertise [45,46].

In line with previous research [46,52], the research team utilized established criteria and points to determine if a participant is qualified as an expert. Hallowell and Gambatese [46] suggest that panelists score at least 11 points to meet the minimum level of qualified expert panelists using the system point based on the following criteria.

- Highest degree (cumulative): BS: 4 points; MS: 2 points; PhD: 4 points
- Years of professional experience: 1 point per year
- Professional affiliations or registrations: 3 points for each valid registration/affiliation
- Member of a committee related to the topic: 1 point per committee membership
- Number of employees and/or students supervised: 1 point for 10 employees and/or students
- Academic or industry publications related to the topic: Book/book chapter: 4 points; academic journal paper: 2 points; conference paper: 1 point; industry publication: 1 point
- Work positions or roles related to the topic: 3 points for each position or role

Using the above criteria and points, along with the demographic information provided by the potential panelists, all participants were found to be qualified as experts except two participants (who scored less than 11 points. Thus, the two participants were dropped from participation in the research, leaving 14 members on the initial expert panel.

2.3.3. Delphi process

Delphi Round #1: The survey aimed to verify the relationship between the task-related constituents and ME, quantify the level of impact that each constituent has on the level of ME, and determine if each constituent has an increasing or decreasing impact on ME. It should be noted that ME was used as a proxy for MWL in the survey. The survey questionnaire for this round included two parts. The first part was designed to capture the qualifications of the panelist to confirm that they meet the criteria set forth for experts. The second part asked the panelists to verify the energy constituents and indicate the level of impact that each of the 14 constituents has on ME.

Delphi Round #2: The objectives of the second survey were to (1) verify the level of impact that each constituent has on ME (confirm consensus amongst the panelists); and (2) identify potential components that can be used to measure each constituent. To achieve the first objective of this round, the researchers allowed the participants to revise and update their response from Round #1 in light of the overall Round #1 results from the entire panel.

Delphi Round #3: The objectives of Round #3 were to (1) finalize the list of applicable components for each constituent and (2) assign a weighting to each component that indicates the level of impact each component has on its applicable constituent. If a component's level of impact was rated as being moderate, high, or extreme (median impact rating of 5, 6, or 7 on the 7-point Likert scale, respectively), and the standard deviation indicated consensus ($SD < 1.64$), the component was deemed to be impactful and thus included in the final ME model. Otherwise, the component was removed from the list.

Delphi Round #4: The objective of this round was to verify the utility of the energy formulas that were previously developed (and revised) to calculate the level of ME that a worker feels when working on a construction site. In this round, the study used validation from experts in academia and industry with an average of 18 years of experience and knowledge about the topic to verify and ensure that the conceptual model is accurate and applicable. Specifically, the experts were asked to indicate their level of agreement with nine confirmation questions regarding the validity of the energy model that was developed using a Likert scale where 1 is strongly disagree, 5 is strongly agree, and 0 indicates "I do not know").

2.4. Research analysis approach

2.4.1. Impact analysis

The panelists were asked to indicate the impacts of the constituents and components on ME using a Likert scale with 0 for no impact, 1 for minimal impact, and 7 for extreme impact. Two types of Likert scales were adopted in the study: a 0–7 scale for the level of impact (Round 1 through Round 3) and a 0–5 scale for the level of agreement among panelists regarding the model (Round 4). As suggested in previous studies [46,53], and given the relatively small number of data points, the researchers used the median response value to determine the level of impact of each constituent and component on ME. The median is less susceptible to influence by biased results and outliers; thus, the median is a more accurate and appropriate measure to evaluate centrality for small data sets [49]. A high median impact rating suggests that the panelists believe the assessed constituent or component has a high impact on the ME felt by a worker. Using the 0–7-point Likert scale, a minimum median value of 5 was set as the cut-off for retaining a constituent and component to quantify the level of ME felt by a worker to ensure that only essential constituents and components were included in the final model, thereby simplifying the final model by reducing the number of constituents to be assessed.

2.4.2. Consensus assessment

One of the more challenging characteristics of the Delphi process is reaching consensus. Standard deviation (SD) is typically used to quantify differences from centrality [46,54]. Hence, SD was used to reflect the variability between panelist responses and, therefore, to measure consensus. A low SD indicates that the rating tends to be close to the median value. An SD below 1.64 was deemed to indicate consensus, as recommended by Rogers and Lopez [55] and Karakhan et al. [49]. In addition to using the SD, the levels of agreement between participants (reliability in the aggregated responses) in the second, third, and fourth rounds of the Delphi process were assessed with the intraclass correlation coefficient (ICC). The ICC was utilized to assess the interrater reliability (IRR) among experts for each round. ICC is a value between 0 and 1, where values below 0.5 indicate poor reliability or consistency, 0.5–0.75 indicates moderate reliability and consistency, 0.75–0.9 suggests good reliability, and values above 0.9 indicate excellent reliability [56]. In line with a recent study by Shrestha and Shrestha [57], the research team decided to use ICC values ranging between 0.6 and 1.0 as an indication that there was reasonable consensus among the expert panelists. Any constituents and components with a median impact rating less than 5 (Moderate Impact) and an SD greater than 1.64 were removed from the list. However, constituents and components with median impact ratings of 5 and above and variability above the SD and ICC thresholds were retained and re-evaluated in subsequent rounds.

3. Results

3.1. Conceptualizing the energy-based assessment model

A detailed review of the literature revealed multiple constituents/factors that affect the level of ME felt by workers as they perform their work [9,39,58–65]. Nnaji [66] proposed that the constituents of energy (key factors that can impact a worker's ability to perform work) consist complexity of the task, uniqueness of the task, predictability of the task, repetitiveness of the task, availability of needed

Table 1
Energy constituents.

Constituent	Description
Task Complexity	The mental and physical demand related with a work assignment differs from task to task. In some cases, a task is multifaceted, intricate, and complicated, and may require significant thought and special skills to perform. Tasks that are highly complex can exist on any type of project.
Task Uniqueness	Some tasks required to produce a project differ from regularly performed work and are unique to the project. Constructions employees who lack of experience may not be familiar with performing such unique tasks.
Task Predictability	The construction often incorporates uncertainty in the work performed. While processes have been developed to simplify and streamline activities, some tasks associated with an activity may be unpredictable due to a lack of information about the task, a lack of requisite skills by the workers, or uncertainty about the jobsite conditions, and other work operation condition (e.g., unpredictability of the work tasks due to unknown information).
Task Repetitiveness	If a task is required to be executed often by a worker, the worker will find the task to be repetitive and may feel differently about the task compared with other less repetitive tasks performed. Difference in task performance may be a result of familiarity (learning curve) developed over time.
Availability of needed resources	Resources (e.g., materials, equipment, labor, etc.) are a significant part of all construction projects, and resource availability is a critical factor for the work to be accomplished.
Task Duration	Each task on a project is typically assigned a duration. This duration helps management verify the progress of a project. In certain cases, the prescribed duration of a task could impact the worker's mental state (e.g., if the required task duration is reduced significantly to accommodate a change in project schedule)
Time remaining to complete the task	In most cases, workers have several tasks lined up to work on for a project. Each task should be completed within a specific duration. However, as workers approach the stipulated completion time, they could be under additional pressure due to the amount of work still to be completed within the time remaining to complete that task.
Crowding	Performing work on a construction site requires space to bring in materials and equipment and perform the required work operations. A construction site may become crowded if many multiple crews and/or different trades are required to work in the same area on the project within a specified timeframe. The size and location of the work area may also increase or decrease the extent of crowding experienced on a project.
Coordination	Coordination of the work plays a vital role in executing a construction project since it helps to reduce space and operational conflicts and enhances teamwork and collaboration. At a task level, coordination might make executing a task more efficient.
Task Value	All tasks on construction projects are valuable since they consume resources and contribute to completion of the project. In addition to the cost and resources used/consumed, the value of a task can vary depending on its complexity, criticality (relative to the critical path), and the type and availability of labor and equipment required to complete the task. Hence, the value of a task could impact a worker's mental state on a project.
Interruptions	While a worker is working on an activity, he/she may need to stop in order to talk with a fellow employee, attend to problems related to the project, replenish material stockpiles, assist an inexperienced crew member, attend to personal business, etc. The interruptions could be internal or external to the project.
Distractions	While conducting their work task, workers may be mentally distracted by the surrounding work conditions, personal interactions with others on or off the jobsite, or other issues of concern. In addition, a distraction can be anything that inhibits workers from paying attention to the task or duty. (e.g., adverse weather condition).
Task Pace	Productivity is an important factor that drives work execution. The pace of the work is considered as the time taken to perform a specified amount of work. A higher pace of work means more work is being accomplished in a given period of time
Switching between tasks	Some workers may be assigned multiple tasks to perform. In some cases, the timing of the tasks may overlap. Switching between tasks occurs when a worker attempts to go from one task to another to accomplish both during the same time period. Switching may also occur when a worker is given new tasks very frequently during the work shift.

resources, duration of the task, time remaining to complete the task, crowding, coordination, value of the task, interruptions, distractions, pace of the task, and switching between tasks. Table 1 provides a brief description of each of the 14 constituents. It is important to note that these constituents influence MWL differently. While some constituents are expected to increase the level of MWL (complexity, etc.), some will reduce the MWL felt by workers (e.g., availability of resources). Therefore, it is important to identify or develop a reliable process for combining these constituents to support the quantification and assessment of MWL. To create this process, the researchers discretized these constituents using the primary forms of energy: kinetic and potential energy.

3.1.1. *Formulation of kinetic energy and potential energy for construction operations*

Different types of energy exist, such as gravity, thermal, radiant, chemical, nuclear, and electrical. However, following closer observation of the properties of various forms of energy, scientists believe that the types of energy can be classified into two categories: kinetic energy and potential energy [67]. Every type of energy associated with motion is called kinetic energy (KE), and energy associated with the position of an object is called potential energy (PE) [68]. Given these definitions, the current study focuses on energy through the lenses of these two extensions: kinetic and potential energy. To estimate the level of ME felt by a worker when performing a construction task, it is important to formulate equations for both KE and PE that include the constituents described in Table 1. These energy types can be defined with respect to this context as:

Kinetic Energy (KE): The work expended while performing a task. Kinetic energy consists of two components that symbolize mass and velocity in the conventional formulation of KE.

i. *Nature of the task (NT)* reflects the inherent, internal characteristics of the task that affect the level of energy [39]. NT mimics mass in the classical mechanics equation for calculating KE.
ii. *Execution of the task (ET)* represents the external impacts resulting from the surrounding environment and chosen means and timing of the task performance. ET is linked with the dynamic execution of the task and mimics velocity in the classical mechanics KE equation.

Potential Energy (PE): The concept of potential energy can be used in the construction industry to describe the effect of an upcoming task (work) that has already been assigned but is yet to be performed [66]. In the presence context, PE is quantified using NT and the following two additional variables.

i. *Demand to complete all tasks (DCT):* DCT reflects the impact on ME of the relationship between the value of the work (in terms of $ or other unit) and the time available to complete the work [39]. DCT is divided into two parts, which are “Value of all tasks” and “Time to complete all tasks.” DCT mimics gravity in the classical mechanics equation for PE.
ii. *Demand factor (DF):* DF represents the energy created due to the duration of the task and the time remaining to finish the task [39]. DCT is multiplied by DF to obtain the time-weighted impact of a task. DF mimics height in the classical mechanics PE equation.

3.1.2. *Energy assessment model*

As mentioned above, some constituents increase ME while others decrease ME. Equations (1)–(7) show the proposed relationships for quantifying the level of ME based on the constituent values. When applying this concept to the construction industry, kinetic energy is defined as the effort put forth when carrying out a task. To be clear, a number of tasks are necessary to build a project. The definition of a “task" as it relates to construction and the factors that affect completing tasks, as outlined by a number of scholars, should be covered at this point. According to the findings of a study conducted by Nnaji in 2015 [66], every task has its own set of factors that can either enhance or hinder the ability of an individual to complete it successfully. Antunes and Gonzales [58] noted that different factors, such as predictability, uniqueness, and repetitiveness, can significantly affect the performance of workers and projects. The conclusions by Nnaji and Gambatese [39] have significant implications for the proposed kinetic energy equation, which can be calculated as follows:

$$\mathrm{KE} = \sum\nolimits_{i=1}^{n} (\text{Nature of the task})(\text{Execution of the task}) \tag{1}$$

According to Nnaji and Gambatese [39], the nature of the task (NT) refers to the energy-related constituents of a task that affect worker MWL. The constituents of NT are, as indicated in Equation (2), complexity, uniqueness, predictability, and availability of resources. In construction, KE can be thought of as the labor being input to perform a task.

$$\mathrm{NT} = \frac{(\text{Complexity of the task}) + (\text{Uniqueness of the task})}{(\text{Predictability of the task}) + (\text{Repetitiveness of the task})} \tag{2}$$

In addition to the nature of the task, the execution of the task needs to be clarified in terms of kinetic energy. As mentioned above, execution of the task (ET) is a quantifiable sum that refers to the energy associated with constituents connected dynamically to carry out the work. Other factors may be present when executing tasks along with the preceding energy constituents. However, in this study, the constituents that affect how a task is carried out, according to Nnaji [66], are provided in Equation (3) to quantify ET.

$$\mathrm{ET} = (\text{Pace of the task}) \left[\frac{(\text{Crowding}) + (\text{Coordination}) + (\text{Interruptions}) + (\text{Distractions}) + (\text{Switching between tasks})}{(\text{Availability of needed resources})} \right] \tag{3}$$

Potential energy has been described from the construction perspective as the result of a task (work) assigned to a worker, but which has not yet been completed [66]. Additionally, it should be mentioned that a high level of potential energy could put more stress on a worker and increase MWL, which might lead to poor worker performance. Potential energy (PE) has two components that affect how much potential energy construction workers experience. These components include the quantity and kind of tasks that must be completed by a worker as well as the pressure to finish any unfinished duties that have been allocated to the worker. Similar to KE, the first component of PE is NT. The second component is the demand to complete all tasks (DCT). Equation (4) is used to calculate PE. For a solid object, the formal definition of PE in physics includes gravity and height (i.e., from $PE = mgh$). In the energy model, gravity and height are represented by DCT. Consequently, for the energy experienced by a worker executing a construction task, PE can be calculated as follows:

$$\mathrm{PE} = \left[\sum\nolimits_{i=1}^{n} (\text{Nature of the task})\right](\text{Demand to complete all tasks}) \tag{4}$$

According to Nnaji [66], there are two constituents that are believed to have a significant impact on how stressed employees feel. These two constituents are: (1) total job completion time, and (2) task importance. As a result, the energy that a construction worker feels while performing tasks can be affected by the time it takes to complete the tasks. Workers experience feeling anxious and stressed if the tasks are carried out close to the activity's completion deadline. This anxiety is referred to as the demand factor (DF), as seen in Equation (6), and it can affect the efficiency of the project. The demand factor refers to the pressure that accumulates between the present time and the time when the task needs to be completed. A higher DF value creates greater potential energy. But, DF is impacted by the value of the task, where the stress felt by workers is less if the value of the task is less relative to the time remaining to complete the task. The demand to complete all tasks (DCT) is divided into two constituents: value of the task and time remaining to complete the task, as seen in Equation (5). The DCT is then multiplied by the DF to take into account the effects of the task duration.

$$\mathrm{DCT} = \left[\frac{\text{Value of the task}}{\text{Time remaining to complete the task}}\right](\mathrm{DF}) \tag{5}$$

$$\text{Demand factor } (\mathrm{DF}) = 1 + \frac{\text{Duration of the task}}{\text{Time remaining to complete the task}} \tag{6}$$

After kinetic and potential energy are calculated, total mental energy (ME) can be calculated as shown in Equation (7) [69]. ME is then used as a proxy to evaluate the level of MWL experienced by a worker.

$$\text{Total Mental Energy } (\mathrm{ME}) = \mathrm{KE} + \mathrm{PE} \tag{7}$$

The impact of each constituent is assessed using multiple variables (called "components"). In this case, the constituents act as "constructs," and the components act as "items" used to measure the construct. While the researchers believe that the constituents, components, and proposed relationships posited in the seven equations are reasonable, verifying their theoretical and practical relevance is important. Moreover, developing a process for assessing ME using these equations is important. Therefore, the researchers relied on a structured, systematic, and quantitative process to verify the utility of the constituents.

3.1.3. *Assessment metric*

A metric is characterized as a scale used to measure the degree of impact of the component. A weighting is allocated to each metric level to reflect the degree of influence on each constituent. Studies identified through the literature review utilized a linear scale (Likert scale) to assess cognitive abilities. For instance, the Profile of Mood States (POMS) [70], MWL status [30], Situation Awareness Global Assessment Technique (SAGAT) [71], and NASA Task Load Index (TLX) [36,37] utilized a 5 to 10-point linear scale (1 = Llow and 10 = high) to measure cognitive state. Consequently, in line with these studies, the research team decided to use a 5-point linear scale for each metric scale where 0 = no impact, 1 = negligible impact, 2 = low impact, 3 = mild impact, 4 = medium impact, and 5 = high impact for a constituent that has an increasing impact on MWL. On the other hand, for a constituent that has a decreasing impact on MWL (i.e., if the constituent value increases, the impact on MWL decreases), the metric scale used was: 0 = no impact, 1 = high impact, 2 = medium impact, 3 = mild impact, 4 = low impact, and 5 = negligible impact. The reason for this alteration is that if the constituent has an increasing impact on MWL, it should be placed in the numerator of the KE or PE equation; otherwise, it is placed in the denominator. It is important to note that the anchors for each scale are dependent on the type of component (see Table 4 in Appendix).

3.2. *Verification of model: delphi results*

3.2.1. *Round #1: verify conceptualized model and quantify impact of constituents on ME*

To quantify the level of impact of each constituent and indicate if the constituent has an increasing or decreasing impact on ME, the Delphi panelists were asked to provide a rating using a Likert scale ranging from no impact (0) to extreme impact (7), and indicate if each constituent has an increasing or decreasing impact on energy. Most panel members indicated that the 14 constituents provide an essential foundation to assess worker perception of mental workload in construction (i.e., median ratings ranged between 5 and 6 based on a 7-point Likert scale). According to the expert panel, the constituents significantly impact the level of ME felt by a worker. Following the Round #1 data analysis, summary data was sent back to the panel members for confirmation and reassessment in Round #2.

3.2.2. Round #2: finalize list of constituents and identify components for each constituent

Fourteen-panel members participated in this round and provided a response. Based on the panelist responses, SDs for all constituents were below 1.64, and the ICC was 0.76 (95 % Confidence Interval Lower Bound = 0.518; Upper Bound = 0.908), representing good reliability and consensus for each constituent. Thus, consensus was reached for all constituents.

The relative weighting of each constituent was estimated using Equation (8). The relative weight indicates how important each constituent is relative to other constituents. A constituent with a median impact rating of 5.5 (complexity of the task, for instance) will have a relative weight of 1.1., while a constituent with a median impact rating of 5 will have a relative weight of 1.0. Table 2 summarizes the results from the Delphi study for each constituent regarding their importance, consensus level, and the nature of the impact (increasing or decreasing) on ME.

$$\alpha_1 = \frac{\text{Constituent impact rating (median)}}{\text{Minimum impact rating for all constituents (median)}} \tag{8}$$

To achieve the identify components that can be used to measure each constituent, the researchers presented the participants with a list of 61 components identified from an extensive literature review related to safety, quality, psychology, human factors, and personnel management [72]. Panel members were asked to rate the relevance of each potential constituent to a specific component using a binary scale (Yes/No). The panelists were also given the opportunity to assign components to each constituent.

In addition to largely agreeing that the 61 components are relevant (86 % minimum agreement rate), the Delphi panel experts suggested an additional 30 relevant components. Therefore, 91 components were confirmed or identified in Round #2. However, developing an assessment model that utilizes all 91 components is challenging and would lead to a very complex tool for the end user. Therefore, to shorten the list of components to those that are most impactful, the panelists were asked in Round #3 of the Delphi process to indicate the level of impact each component could have on a constituent in order to determine whether to retain or delete a component. Also, some components were grouped together and revised to improve clarity and maintain consistency with industry/research terms.

3.2.3. Round #3: finalize components for each constituent

Out of the 14 panel members who participated in Round #2, 13 panelists completed the survey and provided responses in Round #3. In line with the elimination process described in Section 2.3.3, 30 components were removed from the list, and ten were combined with similar components. Fifty-one components met the conditions to be included in the ME model. While the total number of components for each constituent could be reduced to improve simplicity in the model, doing so could have an adverse effect on the accuracy of the level of ME calculated. Also, the ICC for Round #3 was 0.94 (95 % Confidence Interval Lower Bound = 0.753; Upper Bound = 0.998), which indicates excellent reliability/consensus among the panelists in this round.

Next, the relative weights were developed using Equation (9). The weight indicates the level of impact a component has on a constituent [72]. Developing a weight for each component ensures that the final model will account for the relative weights between the components.

$$X_n = \frac{Component\ impact\ rating_n\ \ (median)}{Minimum\ \text{impact rating for all components}\ (median)} \tag{9}$$

3.2.4. Round #4: confirm ME quantification and energy assessment model

Eleven out of the fourteen panelists (79 %) completed the fourth survey round. Although the sample size reduced, which is typical in Delphi studies spanning several months and rounds, 11 responses are within the threshold recommended for the number of panelists [46]. A one-sample Wilcoxon signed-rank test was conducted to assess the effectiveness and utility of the research products and

Table 2
Summary of constituent level of impact and weighting (n = 14).

No.	Constituent	Level of Impact (0 = no impact, 1 = low impact, 7 = extreme impact)			Effect of constituent impact on energy (% of respondents)		ICC	Weighting ($\alpha_1 - \alpha_{14}$)
		Median	Mean	SD	Increase	Decrease		
1	Complexity of the task	5.50	5.21	1.42	100 %	0 %	0.76	1.1
2	Uniqueness of the task	5.00	4.64	1.22	100 %	0 %		1.00
3	Predictability of the task	5.00	4.36	1.22	29 %	71 %		1.00
4	Repetitiveness of the task	5.00	4.36	1.28	14 %	86 %		1.00
5	Availability of needed resources	6.00	5.54	0.78	29 %	71 %		1.2
6	Duration of the task	5.00	5.14	1.23	93 %	7 %		1.00
7	Time remaining to complete the task	5.00	5.21	1.37	43 %	57 %		1.00
8	Crowding	5.50	5.07	1.44	71 %	29 %		1.1
9	Coordination	5.50	5.14	1.17	64 %	36 %		1.1
10	Value of the task	5.00	4.93	1.14	100 %	0 %		1.00
11	Interruptions	5.00	4.93	1.44	64 %	36 %		1.00
12	Distractions	5.00	4.79	1.25	64 %	36 %		1.00
13	Pace of work	5.00	5.14	1.35	93 %	7 %		1.00
14	Switching between tasks	5.00	4.50	1.34	64 %	36 %		1.00

outcome. The test value was set at 2.5, which is the midpoint of the 5-point Likert scale.

The panel members were shown the equations for KE, PE, and total ME, along with descriptions of each equation and the derivation process. The panelists were also given the opportunity to evaluate the energy assessment tool developed as part of this study. The energy model calculations and assessment tool were provided in an Excel spreadsheet to show the panel members how the model could be applied on a construction site in the future. Participants were asked to assess the constituents, components, and metrics included in the assessment tool. Finally, panelists were asked if the energy model could accurately reflect the safety performance of, and level of work quality produced by, a worker while performing a construction task and accurately measure other performance criteria such as productivity, cost, etc. The responses to these Round 4 questions, mean and median ratings, SD, p-values, and ICC, are presented in Table 3. As shown in the table, all median values are 3 or above. More importantly, results from the one-sample test indicates that the median value was significantly above the midpoint of the Likert scale, which implies that panelists confirmed the validity of the research outcome (ME model, components, etc.).

4. Mental workload assessment process

As stated previously, a vital objective of the present study was to develop a method for assessing the MWL felt by workers when performing an activity on a job site. Fourteen constituents and 51 components were identified and confirmed from the literature review and Delphi process to measure the level of ME. Fig. 3 summarizes the process for utilizing the tool developed to assess worker MWL.

The maximum energy level that can be calculated using the linear rating scale from 0 to 5 for each component is 875. This maximum level (875) is achieved if each component receives the maximum negative value for the metric (i.e., the value that leads to the greatest amount of MWL). This maximum level can be achieved if each component for constituents such as Complexity of Task and Distraction are rated 5 (maximum negative metric on the scale), while components for constituents such as Availability of Resources receive a rating of 1 (“1” denotes lack of resources, which is negative and increases the ME felt by a worker). In contrast, the minimum total ME that can be calculated is 1 if the values of the metric are given the smallest weighting value (or most positive value). Equation (10) is used to find the level of MWL, as a percentage, relative to the maximum total ME possible. Additional information on the process for determining the maximum ME level is provided in Ref. [72].

$$\text{Level of MWL} = \frac{\text{Total ME Calculated}}{\text{Maximum Total ME Possible}} \times 100 \tag{10}$$

where: Maximum Total ME Possible = 875.

The level of MWL ranges from 0 % to 100 %, as shown in Fig. 4. While at this point, there are no empirically-supported thresholds for identifying high and low energy levels, based on the present study, the researchers suggest five ranges. The researchers propose that a level of MWL from 0 % to 24 % indicates a negligible level of MWL, level of MWL between 25 % and 43 % indicates a low level, a percentage from 44 % to 62 % indicates a mild level, a percentage from 63 % to 81 % indicates a medium level, and a percentage between 82 % and 100 % indicates a high level. If the level of MWL is measured and identified to be in the high range, a worker who performs the task is expected to feel more MWL and, therefore, a high mental workload. The percentage values of each range rely on the metric values (0, 1, 2, 3, 4, and 5). For example, a metric is given the highest weighting value of 5 for a component whose constituent has an increasing impact on MWL and is included in the numerator of an equation. The metrics that have a decreasing impact on MWL are given the highest weighting value as 1 for the component and therefore the constituent should be placed in the denominator of the ME equations shown above. As a result, the level of MWL will be high if the metric values are given the highest

Table 3
Confirmation of energy model (n = 11).

Confirmation Questions	Median	Mean	SD	*P*-value	ICC
Do you agree that the overall energy model could be applied to measure the level of energy associated with a task (s) on a construction site?	4.00	3.82	0.75	0.003	0.83
Do you agree that Kinetic Energy (KE) can be used as a means to accurately reflect the level of “energy” experienced by workers while performing work?	4.00	3.82	0.60	0.002	
Do you agree that Potential Energy (PE) can be used as a means to accurately reflect the level of “energy” experienced by workers who are assigned work that is yet to be executed?	4.00	3.64	1.03	0.014	
Do you agree that the constituents shown in the Excel spreadsheet can be used as a means to accurately measure the level of energy associated with a task(s) on a construction site?	4.00	4.00	1.18	0.010	
Do you agree that the components shown in the Excel spreadsheet can be used as a means to accurately measure each constituent?	4.00	4.00	0.77	0.003	
Do you agree that the initial metric scale has been developed for each component using a linear scale (e.g., 1, 2, 3, 4, 5) is appropriated for each level in the metric to measure each component?	4.00	3.55	1.04	0.017	
Do you agree that the energy model shown in the Excel spreadsheet will accurately reflect the safety performance of a worker while performing a construction task?	3.00	3.45	0.82	0.002	
Do you agree that the energy model shown in the Excel spreadsheet will accurately reflect the level of work quality produced by a worker when conducting a work task?	3.00	3.45	1.04	0.018	
Do you agree that the energy model shown in the Excel spreadsheet can be used to accurately measure other performance criteria such as productivity, cost, etc.?	3.00	3.55	0.69	0.003	

Note: 0 = I do not know, 1 = strongly disagree, 5 = strongly agree.

weightings. Conversely, if the level of MWL calculated is low (less than 24 %, for instance), the amount of MWL felt by a worker is negligible. The level of MWL felt by a worker is largely dependent on the type of task and accompanying work process and environment.

Following the development and verification of the equations and MWL assessment process, the researchers developed a simple and easy-to-use Excel-based tool to help with implementation in practice. A table showing the constituents, components, and metrics used in the tool and how they are related is provided in Table 4 (Appendix).

5. Discussion

This study aims to develop a new method using the concept of energy to predict a construction worker's MWL during work activities by addressing the major characteristics associated with the work task, such as complexity, repetition, and switching between tasks. Besides the design of the model, the researchers also analyzed the various factors that affect implementation of tasks. To ensure consistency in the structure of the energy model, constituents and their definitions were identified based on the literature. Panel members were then asked to provide the level of impact that the constituent has on the level of ME and to indicate if the constituent has an increasing or decreasing impact on ME. The panel members agreed that the constituents are an essential foundation to assess and evaluate MWL and worker performance in construction. However, some panel members suggested that other factors, such as communication, worker experience, and planning, could impact MWL.

The results of Delphi survey provide initial evidence of the validity of the proposed model using the energy concept. The model proposed by the study could be used to measure the level of MWL that an individual's task generates on a construction site. The result also suggests that the kinetic energy (KE) value could be used to accurately reflect the level of energy that workers experience while performing their duties. The concept of KE is used in construction to refer to the work that is done in carrying out a task. The performance of a project is measured, in part, by the total number of tasks that can be completed within the project's parameters. There are many kinds of tasks that are involved in a construction project; however, various factors can affect the ability of a worker to complete a task. A comprehensive review of literature revealed that certain factors can influence the output of workers [58,61]. These factors were identified as task-specific factors. On the other hand, within the energy model, the potential energy associated with a task is considered as the effect on MWL of the work that has been assigned to the worker, but is not yet completed by the worker. According to Delphi experts, a high level of potential energy can lead to poor performance. The time available to complete a task and the duration of the task were identified as constituents that greatly impact the potential energy felt by construction personnel on a project. The

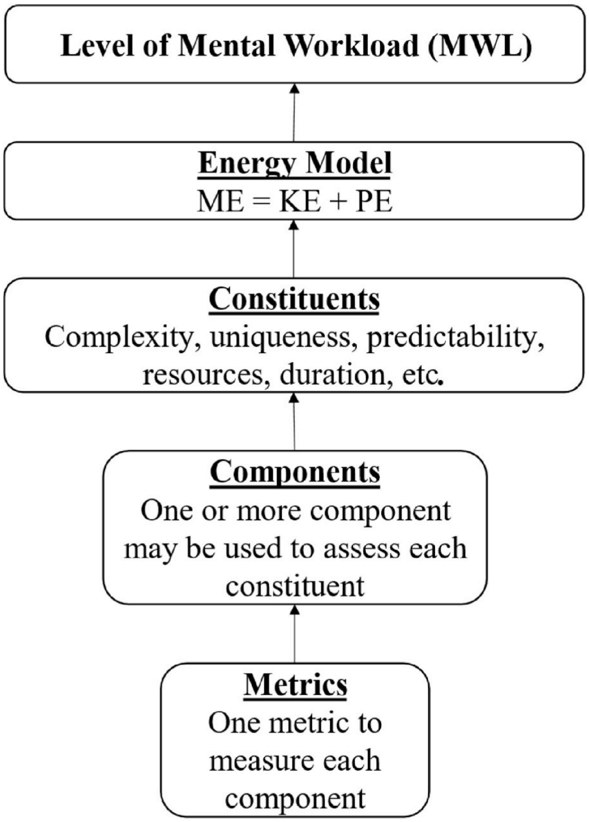

Fig. 2. Structure of energy assessment model.

number of tasks a worker has to complete within a certain period of time can also affect their MWL levels, leading to poor performance. Zhang et al. [73] revealed that a short duration to complete a task could lead to mental fatigue and cognitive demand, preventing workers from correctly identifying hazards and performing construction activities.

Multidimensional approaches (i.e., NASA-TLX, SWAT) offer useful diagnostic information on the mental workload of sources, but these instruments do not provide researchers and practitioners with information about the attentional resources required for a specific task level [74]. Unlike other models, the main objective of the energy model was to provide a tool that would enable objectively measuring MWL based on how demanding the task is. Other current instruments/models do not evaluate MWL in light of the specific and manageable features associated with construction tasks. The characterization of the energy-based model also indicates that constituents (e.g., complexity of the task of the task, distraction) are essential to determining MWL in the construction industry. In the present study, the model developed is also organized into a three-level hierarchy to measure ME based on task characteristics in order to assess MWL, as seen in Fig. 2. Constituents and components constitute qualitative descriptions of tasks on construction sites while metrics are used to quantify an existing level of work components. The developed model also aims to evaluate the effects of various factors on the MWL felt by workers by focusing on the perception of workload and task-level factors.

The proposed approach can also help to improve the efficiency of construction projects by identifying the factors that contribute to the safety of workers and work quality. For example, some construction tasks have high mental requirements that can be as demanding as those that are physically demanding. According to the Task Demand-Capability (TDC) model developed by Mitropoulos et al. [75], if the demands of a task exceed the capability of the workers to perform the task, the loss of control can lead to various problems, such as accidents and quality defects. Therefore, the proposed model provides a predictive tool to assess construction worker MWL based on task level and behavior.

Finally, the results of the study indicate that the energy model mainly reflects the amount of information and activities present, and their impacts on worker safety performance and the work quality produced by a worker when conducting a work task. While the model targets safety and quality, it does not reflect potential impact to other performance criteria such as productivity and cost.

6. Contributions to research and practice

The present study contributes to *knowledge* in the areas of construction management and human factors by identifying and assessing task-related factors (constituents and components) that impact the level of MWL felt by workers and, as a result, worker performance. The study utilizes a novel process to theorize and conceptualize a potential critical mediator (mental energy) that could help increase an understanding of the relationship between these factors and MWL. The model is also the first of its kind to identify and assess energy constituents, components, and metrics, which are critical to accurate assessment of cognitive attribute. In addition, the study contributes to practice by developing a method for assessing the influence of MWL with respect to safety and quality, which utilized constituents, components, and metrics. This approach was validated by experts from academia and industry who have extensive knowledge and experience in the topic, ensuring face reliability and accuracy. Therefore, the study contributes to construction *practice and research* by proposing and developing a novel, proactive method using the energy concept for assessing the potential impact a task and associated work conditions could have on a worker's MWL.

7. Conclusions and future research

The present study aimed to develop an initial, novel process for evaluating the impact of task and project related factors on a construction worker's MWL using energy as a framework. The present study was also designed to identify and confirm factors that impact worker MWL, characterize the potential value of an energy-based assessment model, and develop a tool for measuring worker MWL using the energy model. The study identified 14 constituents, 51 components, and a verified metric for measuring each component. These results were incorporated into the proposed energy assessment model to evaluate the level of mental workload experienced by a worker. Insights from experts were used to develop weights for each constituent based on the potential level of impact on MWL. Generally, the Delphi panelists agreed that the constituents could significantly impact the MWL felt by a worker depending on the task scenario.

Although the present study advances knowledge and practice, it has several limitations that could be addressed in future studies. The energy model considers factors related to a task or project, but does not include individual factors that can affect the perception of MWL. Future studies could assess the role of a worker's skill, knowledge, and capability on MWL. Although the initial model was not subjected to empirical data validation, the development of the energy model and assessment process is expected to be the foundation for future studies on energy-based assessment in the construction industry. However, application and implementation of the developed model are needed to ensure that the tool can be easily applied to different types of tasks. Future research is needed to apply and test the model on a construction site. Utilizing this model in a case study would be beneficial as part of the future research. Also, the current

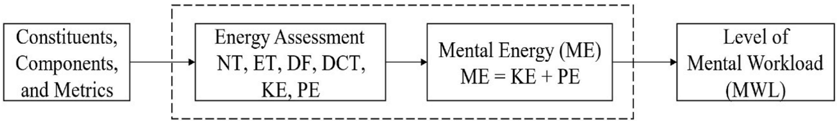

Fig. 3. Energy model process.

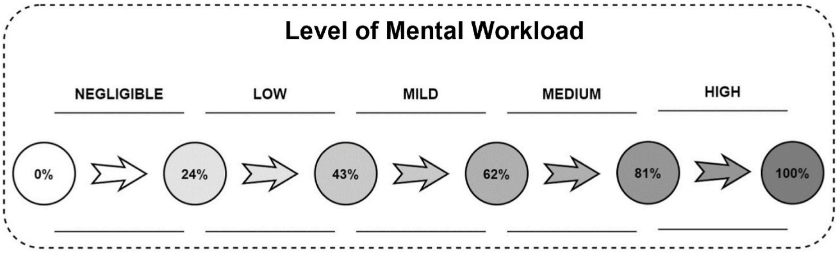

Fig. 4. Level of mental workload.

study utilized the Delphi technique to develop the energy model rather than an experimental approach involving human subjects. Although this choice was an ideal fit for developing foundational insight guided by construction experts, a research design that relies on an experimental approach may expose other weightings for the components, and mitigating or magnifying effects of the constituents, that would result in a modified, and potentially more accurate model. Additionally, the proposed model has not been thoroughly tested and calibrated in the field, therefore its accuracy and usefulness could be limited. Future studies should be conducted using an experimental method, optimally in both in a controlled environment and in the field, to demonstrate the feasibility and accuracy of the proposed model. The model should also be validated for a range of active projects and work tasks to ensure that it can be used effectively in multiple settings. Regardless of these limitations, the goal of the study – conceptualize an energy-based assessment model for worker mental state and verify the utility of the proposed model – was met following a rigorous research process.

After testing the energy model, a supporting study is essential to examine the correlation between the level of MWL and key performance indicators, such as safety, work quality, and worker productivity. It is expected that such an additional study would help to justify the importance and value of using energy model to assess worker perception of mental workload and generate interest in it. Also, the constituents could be organized into different categories to make them more user-friendly and facilitate project managers and supervisors focusing on a specific group of constituents to lower the amount of MWL, and to indicate that some constituents have a greater impact on safety than quality. Finally, while the researchers elected to use a linear scale for assessing the constituents and components for the present study, future studies could utilize an exponential or other type of scale that may more accurately represent the distribution of impact of the task on the component.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Abdulaziz Alotaibi: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. **John Gambatese:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – review & editing, Validation, Visualization. **Chukwuma Nnaji:** Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Writing – review & editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table 4
Energy Model Structure used in Implementation Tool

Constituent	Component	Metric for Measuring Component (Linear scales: 0, 1, 2, 3, 4, 5)
1. Complexity of the task	1.1 Task size	5 = very large task; 4 = large task; 3 = medium-sized task; 2 = small task; 1 = very small task
	1.2 Quality of pre-planning	5 = very poor pre-planning; 4 = poor pre-planning; 3 = fair pre-planning; 2 = good pre-planning; 1 = excellent pre-planning
	1.3 Task execution difficulty	5 = very difficult to execute task; 4 = difficult to execute task; 3 = moderately difficult to execute task (routine manner); 2 = somewhat difficult to execute task; 1 = little difficulty to execute task

(*continued on next page*)

Table 4 (*continued*)

Constituent	Component	Metric for Measuring Component (Linear scales: 0, 1, 2, 3, 4, 5)
	1.4 Number of steps/Level of accessibility	5 = extreme number of steps; 4 = high number of steps; 3 = moderate number of steps; 2 = slight number of steps; 1 = low number of steps; 0 = one step
	1.5 Level of physical strain/exertion	5 = extreme exertion; 4 = very intense exertion; 3 = moderate exertion; 2 = some exertion; 1 = light exertion; 0 = no exertion at all
2. Uniqueness of the task	2.1 Skills/experience needed to perform the task	5 = extensive skills; 4 = high level of skills; 3 = moderate skills; 2 = minimal skills; 1 = little to no skills
	2.2 Worker familiarity with task	5 = no experience; 4 = minimal experience; 3 = moderate experience; 2 = high level of experience; 1 = extensive experience
	2.3 Industry familiarity with task	5 = not common in industry; 4 = somewhat common in industry; 3 = moderately common in industry; 2 = highly common in industry; 1 = extremely common in industry
	2.4 Project/company familiarity with task	5 = not regularly performed; 4 = performed irregularly; 3 = performed moderately often; 2 = commonly performed; 1 = performed all the time
3. Predictability of the task	3.1 Level of uncertainty about task scope and performance at the start of the task	1 = very high level of uncertainty; 2 = high level of uncertainty; 3 = moderate level of uncertainty; 4 = low level of uncertainty; 5 = very low level of uncertainty
	3.2 Level of uncertainty about task scope and performance during execution of the task	1 = very high level of uncertainty; 2 = high level of uncertainty; 3 = moderate level of uncertainty; 4 = low level of uncertainty; 5 = very low level of uncertainty
	3.3 Predictability of task duration	1 = unpredictable task duration; 2 = low predictability of task duration; 3 = moderate predictability of task duration; 4 = high predictability of task duration; 5 = task duration certain
4. Repetitiveness of the task	4.1 Number of times task is performed	1 = very highly repetitive task; 2 = highly repetitive task; 3 = moderately repetitive task; 4 = low amount of repetition; 5 = non-repetitive task
	4.2 sub-task length	1 = very long time; 2 = long time; 3 = moderate time; 4 = short time; 5 = very short time
	4.3 Task continuity	1 = very high level of continuity; 2 = high level of continuity; 3 = moderate level of continuity; 4 = low level of continuity; 5 = not continuous at all
5. Availability of needed resources	5.1 Presence of materials, tools, and equipment	1 = very low presence; 2 = low presence; 3 = moderate presence; 4 = high presence; 5 = materials, tools, and equipment present
	5.2 Quality of materials, tools, and equipment	1 = very poor quality; 2 = poor quality; 3 = moderate quality; 4 = good quality; 5 = excellent quality
	5.3 Presence of labor force/crew members who can perform the task	1 = very limited labor force/crew members present; 2 = low presence; 3 = moderate presence; 4 = high presence; 5 = all labor force/crew members needed are present
	5.4 Presence of capable supervisor	1 = no capable supervisor present; 2 = low presence; 3 = moderate presence; 4 = high presence; 5 = capable supervisor always present
6. Duration of the task	6.1 Time required to complete the task	5 = very short required time; 4 = short required time; 3 = moderate amount of required time; 2 = high amount of required time; 1 = very high amount of required time
	6.2 Time available to complete the task	5 = very short available time; 4 = short available time; 3 = moderate amount of available time; 2 = high amount of available time; 1 = very high amount of available time
	6.3 Availability of a time buffer/contingency	5 = no buffer; 4 = minimal buffer; 3 = moderate buffer; 2 = high amount of buffer; 1 = extensive buffer
7. Time remaining to complete the task	7.1 Time available to finish the remaining parts of the task	1 = very short amount of time available; 2 = short amount of time available; 3 = moderate amount of time available; 4 = long amount of time available; 5 = very long amount of time available
	7.2 Need for overtime work to complete the task	1 = very excessive overtime required; 2 = excessive amount of overtime required; 3 = moderate amount of overtime required; 4 = small amount of overtime required; 5 = minimal amount of overtime required
	7.3 Project completion date/Facility opening date	1 = very short time until opening date; 2 = short time until opening date; 3 = moderate amount of time until opening date; 4 = long time until opening date; 5 = very long time until opening date
8. Crowding	8.1 Number of different subcontractors, workers, or crews/trades on site at the same time	5 = very high number on site at the same time; 4 = many on site at the same time; 3 = moderate number on site at the same time; 2 = few on site at the same time; 1 = very few on site at the same time
	8.2 Number of different tasks/activities in the same work area	5 = very high number in the same work area; 4 = many in the same work area; 3 = moderate number in the same work area; 2 = few in the same work area; 1 = very few in the same work area
	8.3 Size of work area relative to the number of workers and size of crew present	5 = very small size of work area; 4 = small work area; 3 = moderate size of work area; 2 = large work area; 1 = very large work area
	8.4 Amount of materials and equipment present in the work area	5 = very large amount presents in the work area; 4 = large amount presents in the work area; 3 = moderate amount presents in the work area; 2 = small amount presents in the work area; 1 = very small amount presents in the work area

(*continued on next page*)

Table 4 (*continued*)

Constituent	Component	Metric for Measuring Component (Linear scales: 0, 1, 2, 3, 4, 5)
	8.5 Presence of materials and equipment in the work area	5 = very high presence in the work area; 4 = high presence in the work area; 3 = moderate presence in the work area; 2 = low presence in the work area; 1 = very low presence in the work area
9. Coordination	9.1 Amount of pre-planning conducted	5 = very small amount of pre-planning; 4 = small amount of pre-planning; 3 = moderate amount of pre-planning; 2 = large amount of pre-planning; 1 = extensive pre-planning
	9.2 Amount of job site management of tasks	5 = very small amount of job site management; 4 = small amount of job site management; 3 = moderate amount of job site management; 2 = large amount of job site management; 1 = extensive job site management
	9.3 Quality of job site management/details	5 = very poor quality of job site management/details; 4 = poor quality of job site management/details; 3 = moderate quality of job site management/details; 2 = good quality of job site management/details; 1 = excellent quality of job site management/details
10. Value of the task	10.1 Value of task outcome to worker/crew	5 = very high value of task outcome; 4 = high value of task outcome; 3 = moderate value of task outcome; 2 = low value of task outcome; 1 = very low value of task outcome; 0 = no value of task outcome
	10.2 Value of the equipment/materials used for the operation	5 = very high value; 4 = high value; 3 = moderate value; 2 = low value; 1 = very low value
	10.3 Significance of the task to the timely completion of the project (i.e., on the critical path or not)	5 = very high significance of task; 4 = high significance of task; 3 = moderate significance of task; 2 = low significance of task; 1 = very low significance of task; 0 = no significance of task
	10.4 Significance of the task to successful completion of the project	5 = very high significance of task; 4 = high significance of task; 3 = moderate significance of task; 2 = low significance of task; 1 = very low significance of task; 0 = no significance of task
11. Interruptions	11.1 Availability of construction drawings for reference	5 = very low availability; 4 = low availability; 3 = moderate availability; 2 = good availability; 1 = excellent availability
	11.2 Extent and types of disruption	5 = very significant/impactful extent and types of interruptions; 4 = significant extent and types of interruptions; 3 = moderate extent and types of interruptions; 2 = insignificant extent and types of interruptions; 1 = very insignificant extent and types of interruptions
	11.3 Number of overlapping work activities for crew members	5 = extreme number of overlapping activities; 4 = high number of overlapping activities; 3 = moderate number of overlapping activities; 2 = low number of overlapping activities; 1 = very low number of overlapping activities; 0 = no overlapping activities
	11.4 Quality of detailed design drawings	5 = very poor quality; 4 = poor quality; 3 = moderate quality; 2 = good quality; 1 = excellent quality
	11.5 Frequency and scope of change orders	5 = extremely significant frequency and scope; 4 = highly significant frequency and scope; 3 = moderately significant frequency and scope; 2 = low frequency and impact of scope; 1 = very low frequency and impact of scope; 0 = no change orders
12. Distractions	12.1 Experience of supervisor	5 = supervisor not experienced; 4 = minimal supervisor experience; 3 = moderate supervisor experience; 2 = highly experienced supervisor; 1 = very highly experienced supervisor
	12.2 Frequency of deserved positive feedback (compliments)	5 = no compliments; 4 = very few compliments; 3 = moderate frequency of compliments; 2 = high frequency of compliments; 1 = extensive compliments
	12.3 Night shifts	5 = night shifts very frequent; 4 = night shifts frequent; 3 = moderate frequency of night shifts; 2 = low frequency of night shifts; 1 = very low frequency of night shifts
	12.4 Weather conditions	5 = extreme weather conditions; 4 = significant weather conditions; 3 = moderate weather conditions; 2 = minor weather conditions; 1 = minimal weather impacts
13. Pace of the task	13.1 Required production rate (e.g., ft/hr, cy/hr, etc.)	5 = very high production rate required; 4 = high production rate required; 3 = moderate production rate required; 2 = low production rate required; 1 = very low production rate required
	13.2 Frequency of rework	5 = very high frequency of rework; 4 = high frequency of rework; 3 = moderate frequency of rework; 2 = low frequency of rework; 1 = very low frequency of rework
14. Switching between tasks	14.1 Amount of multi-tasking required	5 = extensive amount of multi-tasking; 4 = high amount of multi-tasking; 3 = moderate amount of multi-tasking; 2 = low amount of multi-tasking; 1 = minimal amount of multi-tasking; 0 = no multi-tasking
	14.2 Rate in which new tasks are given to the workers while performing current task(s)	5 = very high rate of new tasks; 4 = high rate of new tasks; 3 = moderate rate of new tasks; 2 = low rate of new tasks; 1 = very low rate of new tasks; 0 = no new tasks given
	14.3 Frequency of new workers joining the crew (due to absence, promotion, transfer, etc. Of another crew member)	5 = very high frequency of new workers; 4 = high frequency of new workers; 3 = moderate frequency of new workers; 2 = low frequency of new workers; 1 = very low frequency of new workers; 0 = no new workers

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