An empirical framework for the performance-based evaluation of health and safety's contribution to sustainable construction

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The current approach to construction health and safety (H&S) and sustainable construction underestimates the role of production practices and focuses mainly to the formulation of general guidelines and best-practice policies. This paper aims at exploring the role of H&S in achieving sustainability for projects from a different perspective. A conceptual model is formulated, enabling the integration of H&S and sustainability under the prism of productivity. An empirical framework is subsequently presented to evaluate the relationship workers' health, as expressed by their thermal comfort and environmental parameters, in productivity estimation. A structured data elicitation approach is established for conducting valid field measurements. Process mapping and simulation-based analysis is used for the comparative analysis of productivity forecasting models. An exemplar investigation of formwork operations illustrates the applicability of the proposed approach. The main conclusion from the study is that the implementation of the empirical framework enables the creation of foresight in planning construction operations by analysing productivity variations compared to baseline estimates. Thus, the effect of H&S on performance is quantified and the expected productivity variability can be evaluated. It is believed that such an approach provides a more realistic representation of construction operations and improves the accuracy of the estimating process.

Keywords
construction, health, productivity, safety, thermal comfort.

INTRODUCTION

The protection of the workers' well being and the establishment of a safe working environment are key prerequisites for the achievement of sustainability in construction (Rajendran *et al.*, 2009). However, in traditional practice, the issues of Health and Safety (H&S) are addressed by the formulation of general guidelines, best-practice policies and operating procedures (Wang *et al.*, 2006), whereas issues relating to work methods and production practices are often ignored (Mitropolulos *et al.*, 2009). Therefore this paper takes a different standpoint by exploring the role of H&S management in achieving sustainability for projects. A conceptual model comprising nine sustainable performance criteria is formulated, which allows the integration of H&S and green building parameters under the prism of productivity. A performance-based evaluation of the effect of each one of those criteria in the achievement of sustainability is possible through the implementation of an explicit empirical framework. Given that construction productivity is often studied in a fragmented manner, the purpose of the study is to overcome this deficiency. Hence, the proposed empirical framework (i) enables the creation of productivity forecasting models based on empirical data, (ii) delineates the experimental setting for conducting valid productivity measurements in relation to parameters associated with sustainability and (iii) sets out the criteria which will allow the comparative analysis of the produced estimates. An indicative application of the proposed framework is presented for assessing construction workers' H&S through their thermal comfort, which is a key environmental parameter for rating green buildings.

In the remainder of this paper a brief review of pertinent research on sustainable concepts as well as health, safety and green principles is presented along with a discussion on the role of productivity as a performance indicator for sustainability and H&S in construction. Subsequently, the main parameters used for the evaluation of the thermal comfort are explained followed by a discussion on key facts regarding simulation modelling and analysis. A conceptual model is formulated for integrating sustainability and H&S with productivity estimation. To demonstrate how it can be applied in practice, an empirical framework is proposed. An exemplar implementation of the suggested approach is undertaken for formwork operations. Finally, the main inferences are discussed and the conclusions emerging from the study are elucidated.

Integrating health, safety and green principles

Sustainability is an overarching concept that affects, and can be affected by, every aspect of infrastructure development (Sev, 2009), including the delivery of sustainable construction projects. However, what is meant with sustainable construction (SC)? Is it just an interpretation of the general principles of sustainable development (SD) within the construction context? The literature indicates that it is more than that. First of all, a distinction should be made between the concepts of "sustainable construction" and "green construction". "Green construction" is a term used to describe the design and construction practices that impact the environment (Rajendran *et al.*, 2009). Therefore, it can be said that green construction is part of a sustainable construction development scheme, since the latter will include the economic and social aspects in addition to the environmental perspectives of green construction. The measurement of construction projects' adherence to green principles is achieved through the implementation of green rating systems (GRIHA, 2007; GSBC, 2008; LEED, 2009). However, a qualitative comparative evaluation of the United States Green Building Council's (USGBC) rating system (LEED, 2009), the Green Rating for Integrated Habitat Assessment system (GRIHA, 2007) from India and the equivalent system developed by the German Sustainable Building Council (GSBC, 2008) revealed that (Pantouvakis and Panas, 2010): (i) the rating systems address the issues of H&S in a non-systematic and fragmented manner, in the form of guidelines or best-practice approaches; (ii) a direct relationship between H&S and sustainability is found mainly on environmental factors such as air quality or noise reduction; (iii) there is no linkage to operational or working practices, which are key determinants of the H&S status achieved in a construction site; and (iv) No particular reference is made on how to measure the achievement of job-site H&S within the sustainability concept. Therefore, productivity is believed to be a key factor for quantifying the effect of sustainability on construction projects and a tool for estimating the financial benefits resulting from the implementation of a sustainable strategy. Despite their importance, the current approach to construction safety ignores the role of productivity on evaluating job-site H&S (Mitropoulos and Cupido, 2009). As such, coupling H&S strategies and productivity considerations create a platform for shifting current project management perceptions in the pursue of a more sustainable construction environment based on specific and measurable criteria (Chen *et al.*, 2010). Following this brief review, the next paragraph integrates the concepts of sustainability, H&S and productivity within a seamless conceptual framework.

Conceptual model

The proposed conceptual model for the identification of selected H&S factors is illustrated in Figure 1. The model is structured upon the three pillars of sustainability (economical, social, and environmental) and defines a three-fold relationship of productivity to H&S concepts as shown in Table 1. defines groups or "triads" of criteria depending on the viewpoint of the analyst. A brief description of the selected factors is presented below:

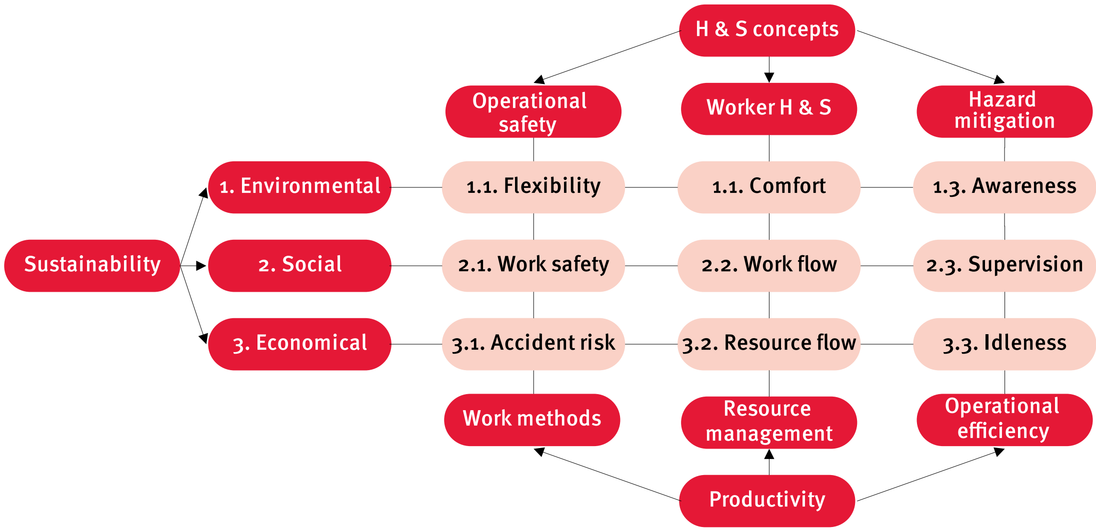


Figure 1. **Conceptual model for sustainable H&S management.**

H&S concept	Productivity concept	Description
Operational safety	Work methods	The working methods are defined by the sequencing of the construction tasks within a specific context. In that sense, they are directly associated with operational safety, since the anticipated production workload determines construction crews' behaviour.
Worker H&S	Resource management	Coordinating and managing the project resources with a particular focus on the site's workforce is linked to the on-site production level and, inevitable, to occupational H&S. Injuries, accidents or fatalities of the workforce do not only cause a severe drop in productivity, but also affect the workers' morale and willingness to perform.
Hazard mitigation	Operational efficiency	Any H&S strategy should be suited for the particular context of the project in hand. Therefore, being able to plan for construction safety means that all necessary measures are taken to mitigate the possible hazards. However, such an approach should guarantee a satisfactory threshold of operational efficiency that, in terms of productivity, would cover the baseline standards.

Table 1. **Association of Health & Safety (H&S) and productivity concepts**

It should be highlighted that the framework is structured in a matrix form and comprises nine performance criteria which are interrelated both horizontally and vertically. For example, if the engineer judges that workers' health and safety is more important and wants to evaluate it under an environmental perspective, then he/she should look at issues relating to their comfort. In that sense, the model

- **1.1. Flexibility:** A given production process (e.g. concrete placing) can be "safe" or "unsafe" depending on how well it adapts to its environment. Therefore, when the method statement is formulated in a way that enables the deviation from normative processes, then operational safety and productivity are increased.
- **1.2. Comfort:** The effect of the environmental conditions on workers' output is of paramount importance. The level of comfort (e.g. thermal, visual) can lead to variations in productivity compared to the baseline estimates. As such, the impact of hot/cold temperatures, noise, lighting, wind and precipitation as key H&S factors must be carefully examined.
- **1.3. Awareness:** All project actors must be aware of the exact work content and be familiar with their working environment. Non-experienced crew members must be given additional attention since a potential

inability to keep up with the pace of works affects their own as well as their colleagues' safety and decreases operational efficiency.

- **2.1. Work safety:** To accomplish good safety performance, it is important to examine work processes before they are implemented. The planned activities should be examined and dangerous work methods must be anticipated to protect the well being of all affected parties (e.g. workers, inhabitants etc.).
- **2.2. Work flow:** The initial schedule is seldom adhered to. As such, when construction work is re-sequenced relative to the planned work sequencing, there can be a significant negative impact on productivity. In addition, schedule changes can lead to concurrent operations which cause congestion if more than one group of workers share the same workspace.
- **2.3. Supervision:** The managerial attitude of the supervisor in directing the workforce and following the work schedule is a critical success factor for satisfying both safety and productivity criteria. Competent personnel can increase on site productivity, whereas, on the other hand, managerial inefficiencies have an impact on both labour- and equipment-intensive operations' efficiency.
- **3.1. Accident risk:** A risk assessment is a prerequisite for identifying potential areas of serious injuries. The financial losses that can incur on a project in case of an injury can be direct (e.g. compensations from claims) or indirect (e.g. interruption of works) and can have a detrimental effect on the project's progress.
- **3.2. Resource flow:** Resources should enter and exit the project according to pre-determined plans. Whether applicable to site personnel or material (e.g. equipment), work continuity must be ensured so as to achieve high resource utilization rates.
- **3.3. Idleness:** The operational delays or interruptions of work affect the project's financial evolution. Furthermore, lost work time leads to schedule acceleration, in order to meet the project's milestones, which has been reported as a major cause of accidents.

It is evident from the analysis that the main objective of the proposed framework is to delineate the taxonomy amongst the different factors and reveal the "hidden" relationships that govern the selected criteria. For that purpose, an empirical framework is presented in the next section, which enables the implementation of the conceptual model in practice.

The proposed empirical framework

The proposed methodological framework enables the investigation of a specific sustainable parameter from a performance-based point of view as shown in Figure 2. It is essentially a four-phase process whose steps are explained in the next paragraphs.

Phase 1 – Preliminary steps: The first phase initiates with the definition of the activity and the respective number of sub-tasks (n_s) required for completing it. In addition, the analyst identifies the risk associated with the activity along with a classification of possible accidents. Using risk taxonomies included in industrial classification codes, the estimator evaluates the safety demand imposed on the respective labour crew for a given operation. In other words, the safety demand reflects the added difficulty imposed on a crew when executing a work task, due to deviations from the normative activity description in comparison to the job in hand.

Phase 2 – Forecasting productivity model: The definition of the operational setting enables the creation of a forecasting model based on historical data. These data serve as a basis for the definition of the Baseline Reference Productivity (BRP), namely each activity's cycle time per unit of measurement (e.g. h/m^2). However, for every standard BRP estimate allowances have to be added to reflect possible losses in productivity due to the peculiarities of the current construction operation, since past construction operations can never be replicated in the exact same way in future projects. For the current study the induced productivity losses are represented by an empirical efficiency factor (E), which can be either a constant value or a distribution taking values in the range of [0,1]. The expected productivity (EP) of each activity is established as a sum of the respective EP of all its sub-tasks. In case only a cumulative productivity estimate for the entire activity is available, sub-tasks productivity is specified according to empirical rules. Finally, the expected conditions for the estimation of the selected Sustainable Performance Criterion (SPC) are defined based on previous experience or historical data.

Phase 3 – Empirical productivity model: This is a parallel phase to the one before, aimed at delineating the experimental framework for the evaluation of the relationship between the chosen SPC and productivity. First, the operational reference conditions are defined (e.g. building element, crew characteristics, shift), followed by a specification of the SPC parameters that are going to be measured. Then, work studies are undertaken to elicit productivity data and measure the SPC parameters by the use of appropriate instrumentation. The collected data is categorised in clusters based on the number of measurement parameters defined for each SPC. In case a statistically sufficient amount of data is contained in each cluster, then probabilistic analysis determines the distribution of the activities' duration. On any other case, supplementary data has to be provided, otherwise the operational setting represented by the specific data cluster cannot be qualified for modelling and analysis.

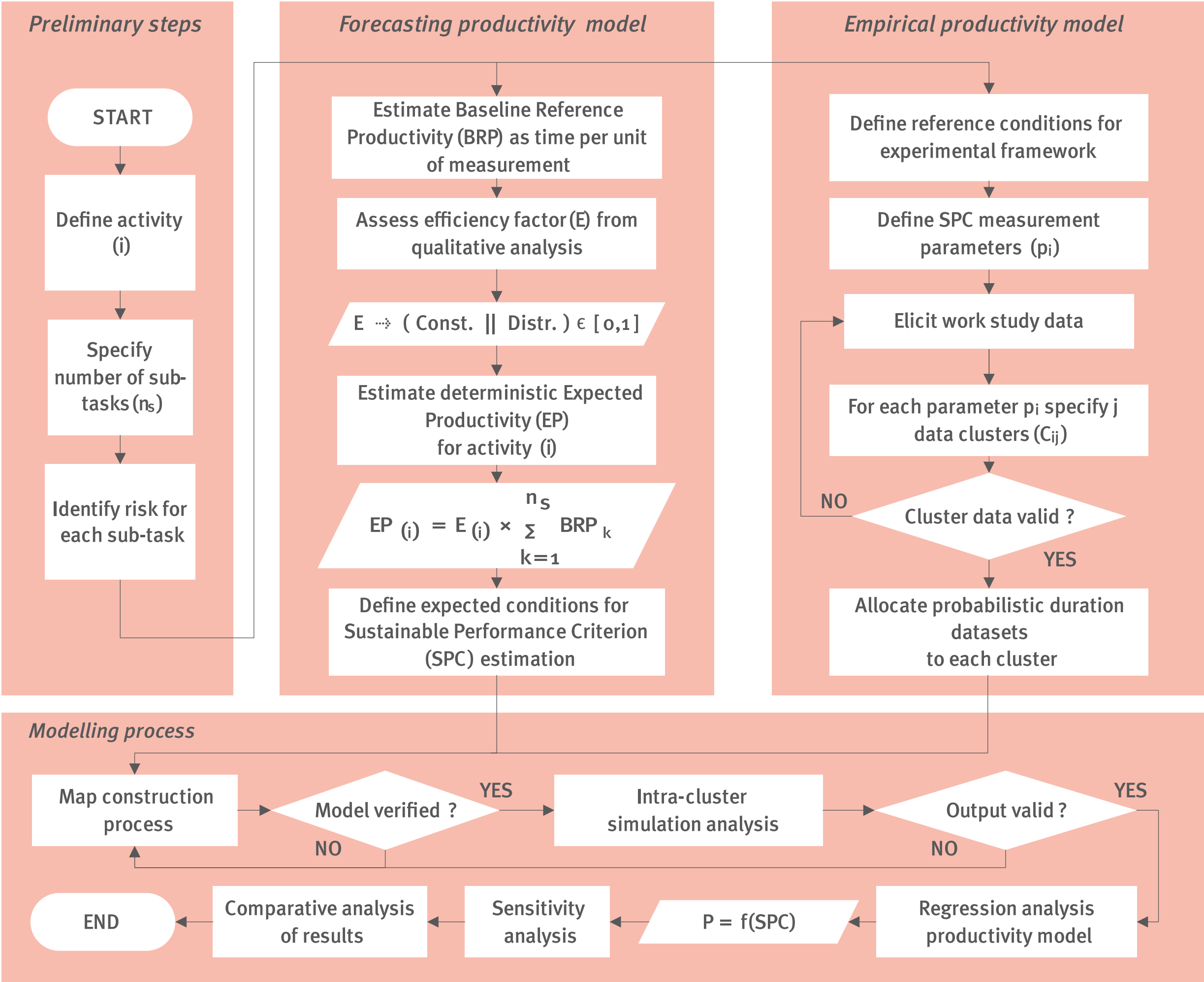


Figure 2. **The proposed empirical framework.**

Phase 4 – Modelling process: The modelling phase commences with the mapping of the construction processes. Simulation models are created for every cluster's dataset and intra-cluster analysis is undertaken to compare the results. In the case of the forecasting productivity models, simulation is used to generate productivity outputs based on BRP inputs, whereas for empirical models, activities' durations are assumed to be probabilistic. Simulation output is validated and a regression analysis between the SPC and productivity is undertaken. Key parameters are varied to evaluate the system's sensitivity and the comparative analysis of the results finalises the investigation.

At this point, two important issues should be clarified. First, in this study, construction operation analysis and process mapping is based on the STRBOSCOPE simulation language and simulation models for productivity estimation are created with the EZStrobe simulation package (Martinez, 2001), whose basic modelling elements are depicted in Table 3 below.

The investigation of PMV's role as a health metric in productivity estimation is undertaken for both the deterministic and stochastic analysis approach. Deterministic simulation models utilize published historical productivity data (e.g. RSMeans (2009) price book), so as to determine the cycle time duration for specific construction activities. Given that deterministic analysis assumes 100% work efficiency, the deterministic simulation models use an efficiency factor whose value is specified by the estimator to represent the subjective effect of qualitative variables on productivity (Zayed and Halpin, 2004), such as safety risk. On the other hand, stochastic analysis is based upon probabilistic data sets stemming from on-site measurements by the use of established work study methods (Alfeld, 1988). In order for both the deterministic and the stochastic approaches to be comparable, the same output analysis method is deployed: each simulation run set comprises of 40 replications at a 95% confidence level, resulting in an unbiased point estimator of average productivity. More details on the proposed empirical framework are provided in the next section.

Second, in the next section, the presented framework is going to be deployed for the "Comfort" criterion of the conceptual model (1.2.), which associated workers'

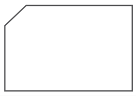
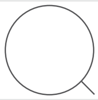
Modelling element	Name	Description
	COMBI	Logically constrained in its starting logic, otherwise similar to the NORMAL element. Always preceded by Queue Nodes.
	NORMAL	Logically unconstrained in its starting logic, indicates active processing of (or by) resource entities.
	QUEUE NODE	Precedes all COMBI activities and denotes the idle state of a resource entity symbolically representing a queuing up or waiting for use of passive state resources.
	ARROW	Indicates the logical structure of the model and direction of entity flow.

Table 3. **EZStrobe modelling elements**

H&S and resource management strategies under an environmental perspective. In general, it has been long acknowledged that the thermal environment affects labour efficiency and may reduce their productivity (Thomas and Yakoumis, 1987). The effect of the thermal comfort on construction operations has drawn limited attention, hence leaving construction planners or estimators with insufficient information to deal with especially in the design stage (Srinavin and Mohamed 2003). The most widely used thermal comfort metric today is the Predicted Mean Vote (PMV) index (ISO 7730, 2005), which represents the thermal strain based on a steady-state heat transfer between the body and the environment. PMV takes values in the range of ±3 where 0 is the ideal thermal comfort point and +3/-3 denote extreme hot or cold environments respectively. PMV is derived from a steady-state model whose main parameters are summarized in Equations (1) to (5) (ISO 7730, 2005).

$$PMV = \left[0.303 \times e^{-0.036 \times M} + 0.028\right] \times \left\{ \begin{array}{c} (M-W) - 3.05 \times 10^{-3} \times \left[5733 - 9.99 \times (M-W) - p_a\right] - 0.42 \times \left[(M-W) - 58.15\right] \\ - 1.7 \times 10^{-5} \times M \times (5867 - p_a) - 0.0014 \times M \times (34 - t_a) \\ - 3.96 \times 10^{-8} \times f_{cl} \times \left[(t_{cl} + 273)^4 - (t_r + 273)^4\right] - f_{cl} \times h_c \times (t_{cl} - t_a) \end{array} \right\} \quad (1)$$

$$t_{cl} = 35.7 - 0.028 \times (M - W) - I_{cl} \times \left\{3.96 \times 10^{-8} \times f_{cl} \times \left[(t_{cl} + 273)^4 - (t_r + 273)^4\right] + f_{cl} \times h_c \times (t_{cl} - t_a)\right\} \quad (2)$$

$$h_c = \begin{cases} 2.38 \times |t_{cl} - t_a|^{0.25} & \text{for} \Rightarrow 2.38 \times |t_{cl} - t_a|^{0.25} > 12.1\sqrt{v_{ar}} \\ 12.1\sqrt{v_{ar}} & \text{for} \Rightarrow 2.38 \times |t_{cl} - t_a|^{0.25} < 12.1\sqrt{v_{ar}} \end{cases} \quad (3)$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 \times I_{cl} & \text{for} \Rightarrow I_{cl} \le 0.078\,m^2 \cdot K/W \\ 1.05 + 0.645 \times I_{cl} & \text{for} \Rightarrow I_{cl} > 0.078\,m^2 \cdot K/W \end{cases} \quad (4)$$

$$p_a = R_h \times 10 \times EXP\left[(16.6536 - 4030.183)/(t_a + 235)\right] \quad (5)$$

where M=metabolic rate [W/m²]; W=effective mechanical power [W/m²]; I_{cl}=clothing insulation [m²·K/W]; f_{cl}=clothing surface area factor [-]; t_a=air temperature [ºC]; t_r=mean radiant temperature [ºC]; v_{ar}=relative air velocity [m/s]; p_a=water vapour partial pressure [Pa]; h_c=convective heat transfer coefficient [W/m²]; t_{cl}=clothing surface temperature [ºC]; R_h=relative humidity [%].

PMV's estimation is possible if six of the above parameters are known (usual values in brackets): metabolic rate (M within 46–232W/m² or 0.8–4.0met), thermal insulation (I_{cl} within 0–0.310m²·K/W or 0–2clo), air temperature (t_a within 10–30ºC), mean radiant temperature (t_r within 10–40ºC), relative air velocity (v_{ar} within 0–1m/s) and relative humidity (R_h within 30–70%) (ISO 7730, 2005). The most relevant research effort to associate PMV with productivity is the regression model developed by Srinavin and Mohamed (2003) for painting, bricklaying and manual excavation operations. However, this model can be criticised for being strictly deterministic, lacking a clear experimental framework and being limited in scope. As such, this study adopts the PMV index within the consistent empirical framework that allows the creation of parametric deterministic and/or stochastic productivity forecasting models that are adjusted to specifically suit the job in hand, as will be shown in the next section.

Exemplar implementation for formwork operations

The proposed methodology is implemented for a hypothetical analysis of foundation walls formwork operations taking place in Athens, Greece. Historical productivity data published by RSMeans (2009) and meteorological data provided by the Hellenic National Meteorological Service (HNMS, 2010) are used for the forecasting models. The development of the empirical models is based on field data provided by Thomas and Yakoumis (1987) with respective rationalization adjustments where appropriate. The application of the steps described in section 4 yields the following results.

Phase 1 – Preliminary steps: The investigation regards formwork operations for basement walls which comprise five (n_s=5) sub-tasks as follows: Fabrication, erection, plumbing, stripping and cleaning. The main risks associated with fabrication are cutting and lifting/lowering of materials, whereas attention should be given to nailing/screwing/drilling operations when erecting the form panels to avoid transportation accidents or overexertion. Plumbing involves using bodyweight, pry bars or other equipment to shift and adjust the formwork which increases the risk of getting caught within the structure. Stripping operations that occur above or below grade typically require workers to ascend or descend ladders to manually transport equipment and materials and relates to the risk of falling on lower or the same level. Form lubrication and preparation involves spraying form oil and/or curing compound, thus exposing labour crews to harmful substances.

Phase 2 – Forecasting productivity model: Each sub-task's BRP is estimated according to formwork operations cumulative productivity data averaged at 1,292h/m² (RSMeans, 2009). The efficiency factor (E) is assumed to take values in the range of 0.75–1.00 following a uniform distribution. Historical meteorological data show that the minimum, average and maximum expected air temperature in March would be 8.4ºC, 12.3ºC and 15.7ºC respectively, with an average humidity of 65,9%. Finally, 35 data points for the PMV index were calculated for gradual variations of t_a.

Phase 3 – Empirical productivity model: Foundation wall formwork executed by an experienced crew in an 8-hour shift is the focus of operations. Equations (1) to (5) were computed in a spreadsheet program and the PMV index was estimated for the six main parameters (M, I_{cl}, t_a, t_r, v_{ar}, R_h) under the following assumptions: The metabolic rate for formwork operations was taken equal to 180W/m² or ~3.1met. Work clothing comprising of "underwear with short sleeves and legs, shirt, trousers, jacket, socks and shoes" (ISO 7730, 2005) was assumed for the whole crew (I_{cl}=1.00clo). Wind velocity was set at 0.25m/s as a representative value of outdoor construction tasks. The rest of the parameters are input variables in the model. One data cluster has been defined for M, I_{cl}, t_a, t_r, v_{ar}, R_h with the respective cluster range being [2.75-3.44met], [0,9-1,2clo], [8.4-15.7]ºC, [11.4-18.7ºC], [0.22-0.27m/s] and [65-67%] respectively. This means that valid comparisons should be undertaken for models comprising data that fit to all of the aforementioned clusters. In any other case the comparison would be statistically invalid since it would represent a different empirical paradigm. The latter is going to be highlighted in the next paragraph. Lastly, field data from Thomas and Yakoumis (1987) representing 35 productivity measurements for formwork operations were processed and the respective PMV values were estimated.

Phase 4 – Modelling process: A generic simulation model was created to represent the construction process, as shown in Figure 3. 35 independent simulation runs were undertaken for the forecasting model and the results are illustrated in Figure 4. A non-linear relationship between thermal comfort and productivity is established, as a means for quantifying the effect of the environment on job efficiency. The forecasting model is consistent with the established notion that the more comfortable the thermal environment (i.e. PMV closer to 0), the more productive a crew can be. Moreover, under the effect of the efficiency factor, simulation-based analysis indicates a drop in optimum productivity of about 10% compared to a 25% decrease in case of a deterministic value. An interesting point of the analysis emerged when an attempt was made to categorize the empirical data into the pre-specified clusters, so as to compare forecasting and empirical models. It was noted that not a single data point from the empirical data set suited the cluster structure of the forecasting one (four data points fitted the t_a cluster but none the R_h cluster). This exemplifies the importance of an explicit determination of the experimental framework, otherwise productivity models of a notably low coefficient of determination (R^2) will be created which, although providing an indication of the productivity threshold, have a limited practical utility (Figure 5). Finally, a sensitivity analysis revealed that the PMV model is particularly sensitive to the metabolic rate, which represents the difficulty of the task being performed.

Discussion

The proposed conceptual model and its respective empirical framework, although still at a development stage, present some distinctive characteristics which could be further elaborated to enhance their practical utility. First of all, the applicability of the conceptual model needs to be further validated, however the fact that both its structure as well as its content have been founded on well established concepts, leads the authors to believe that it can be a practical and useful tool. This is corroborated by the fact that the model induces the safety perspective on productivity, so as to gain a quantitative metric representing the deviation of the adopted construction techniques from process-oriented task execution descriptions.

The aim is to encapsulate the variability of on-site productivity, due to the peculiarities of the construction environment, both from an operational and managerial standpoint. In other words, the inclusion of H&S concepts in construction productivity analysis provides a template for interpreting performance variations. Besides, a given production process can be "safe" or "unsafe" depending on how well it adapts to its environment. Therefore, when the method statement is formulated in a way that enables the deviation from normative processes, then operational safety and productivity are affected.

definition of basic parameters). Even in cases where numerical modelling of factors or variables is not that straightforward, then the judgement of experts should be sought and trusted in interpreting their impact on the investigated operations. This is explicitly demonstrated in the risk identification process, where the risk associated with each sub-task depends on the perceptions of the analyst.

Finally, the modelling process highlights the importance of validity in interpreting productivity estimates. This stage serves the overall objective of the proposed framework which is associated with the conceptualisation of the H&S impact from a productivity-perspective, so as to be able to make informed decisions when needed. By understanding the environmental and operational conditions as well

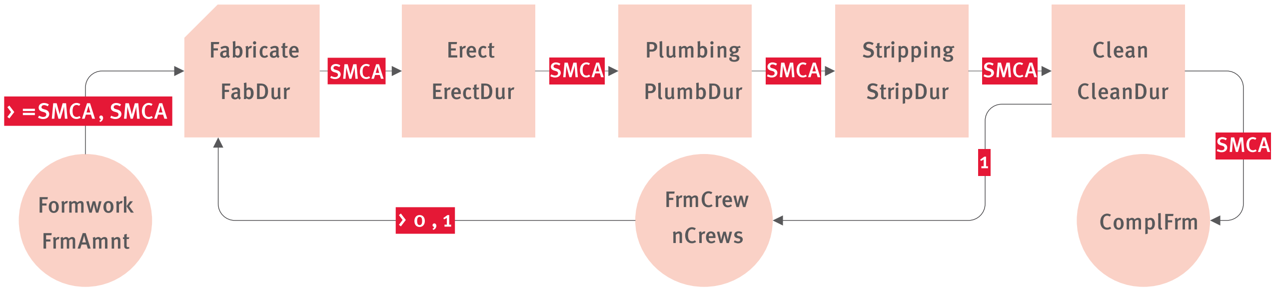


Figure 3. **Generic simulation model for formwork operations.**

Moreover, even though the exact variability magnitude cannot be conclusively determined a priori, since it depends on the site conditions and the activity type which change in a dynamic fashion, the proposed framework serves as a yardstick for benchmarking on-site performance based on a comparative evaluation of theoretical and empirical data. Besides, this is the cornerstone of every project control function, whose responsibility is to alert construction managers to deviations of actual from desired performance.

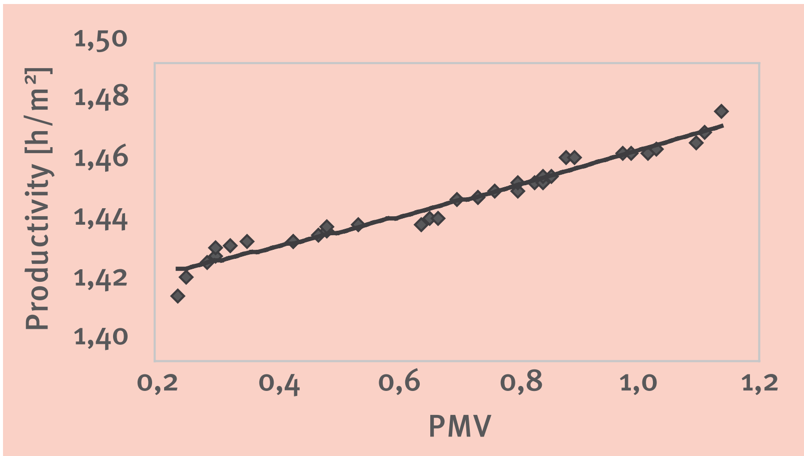


Figure 4. **PMV forecasting model.**

In addition, despite its apparent theoretical or process-oriented nature, the proposed framework should be perceived as a flexible and adaptive tool for construction performance analysis at the activity level. The inclusion of sustainability concepts in construction Health & Safety helps in the formulation of a pluralistic conceptual model that could address variables of versatile nature (e.g. economical, social, environmental). More specifically, although the model's applicability has been evaluated for the PMV index, it is fair to suggest that the other Sustainable Performance Criteria can also be investigated, as long as their impact is mathematically expressed (e.g.

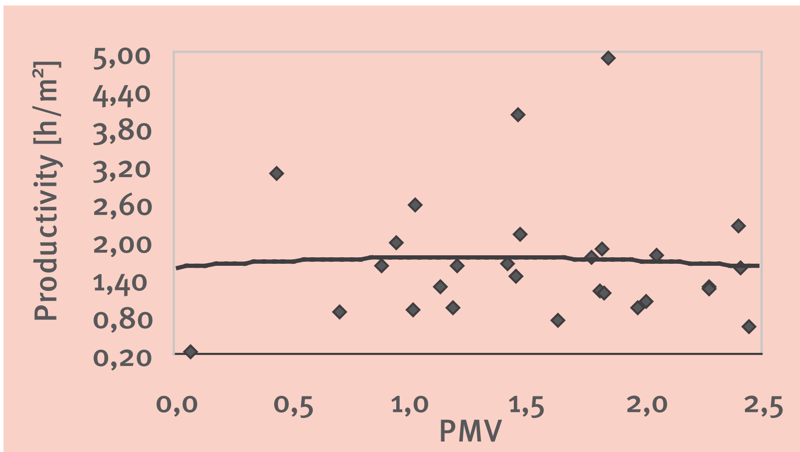


Figure 5. **PMV empirical model.**

as their impact on the investigated system and by ensuring that the outcomes of the analysis bear a high degree of validity, decision risk is minimised, thus resulting in a more decentralised and empowered project environment. Indeed, if an engineer or project manager is equipped with a tool that properly depicts the on-site interactions, then the focus of the decision making paradigm is shifted towards the construction site, where the actual operations are taking place, instead of the higher hierarchical levels, where misconceptions about the project's performance could possibly cause inefficiencies in the execution of the works.

CONCLUSIONS

The presented work demonstrates that construction labour's productivity variation can be interpreted by sustainable concepts pertaining to occupational health and well being, as expressed by the thermal environment. Simulation-based analysis of the impact of thermal comfort on labour productivity creates insight regarding the work practices of construction labour crews, whose behavioural attitude is rarely included in quantitative productivity analyses. The in-depth understanding of the interactions between the investigated factors and productivity is believed to improve decision making, due to the pursued minimisation of uncertainty and safety risk. The use of the PMV index helps in relating key environmental variables to productivity in a directly measurable manner. The current approach emphasizes on the creation of a robust empirical framework that enables the realisation of valid productivity measurements and the subsequent development of comparable productivity models. In addition, the explicit definition of the experimental framework allows the characterisation of each study's applicability and respective scope limitations. The latter contributes to overcoming the methodological inconsistency inherent in many productivity studies, which leads to the creation of fragmented models to the detriment of comparative validity. As such, a more realistic representation of construction operations is achieved which improves the accuracy of the estimating process.

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