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Incorporating the effect of weather in construction scheduling and management with sine wave curves: application in the United Kingdom

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ABSTRACT

The impact of (adverse) weather is a common cause of delays, legal claims and economic losses in construction projects. Research has recently been carried out aimed at incorporating the effect of weather in project planning; but these studies have focussed on either a narrow set of weather variables, or a very limited range of construction activities or projects. A method for processing a country's historical weather data into a set of weather delay maps for some representative standard construction activities is proposed. Namely, sine curves are used to associate daily combinations of weather variables to delay and provide coefficients for expected productivity losses. A complete case study comprising the construction of these maps and the associated sine waves for the UK is presented along with an example of their use in building construction planning. Findings of this study indicate that UK weather extends project durations by an average of 21%. However, using climatological data derived from weather observations when planning could lead to average reductions in project durations of 16%, with proportional reductions in indirect and overhead costs.

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Weather; climate;
construction; schedule;
project delay

Introduction



Many construction projects fail to meet their initially planned completion dates. This is a common phenomenon in many countries and affects almost all kinds of construction works (Alaghbari *et al.* 2007, Mahamid *et al.* 2012, Gündüz *et al.* 2013, Ruqaishi and Bashir 2015).


Lateness (understanding 'late' as missing the originally agreed completion date between the contractor and the project owner) has repercussions for almost all stakeholders (Thorpe and Karan 2008). From the public or private project owner's perspective, late delivery of a project means delaying the start of an asset's operation. This in turn might mean missing a business opportunity, losing a competitive advantage, delaying a return on investment, and ultimately reducing profits (Trauner *et al.* 2009, Głuszak and Leśniak 2015). From the contractors' perspective, late completion might involve contractual penalties and also blocks reallocation of resources for longer periods, limits the resources' productive capacity, and generally increases the contractor's indirect and overhead costs

(Jang *et al.* 2008, Hamzah *et al.* 2011). From the sub-contractors' perspective, late projects generally make resource planning suboptimal as projections for resource demand are inaccurate and thus it is more likely that resource overlaps between multiple projects will occur (Shahin *et al.* 2011). From the end users' perspective, late delivery of projects almost always causes some discomfort and disappointment, particularly if users live nearby and/or are affected by the construction works (Mezher and Tawil 1998).

In some cases, lateness can have certain positive outcomes. For example, activity costs can be reduced to some extent when a longer time span allows for more efficient allocation of resources. However, the benefits of these 'intentional' delays are almost entirely realized by the contractors, and other stakeholders merely experience the negative outcomes.

Among common causes of project delays, weather is consistently rated as one of the most frequent and harmful (Assaf and Al-Hejji 2006, AlSehaimi and Koskela 2008, Orangi *et al.* 2011, Mentis 2015). Weather can impact construction projects in multiple ways: by

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decreasing productivity and sometimes halting construction (Rogalska *et al.* 2006); by ruining unprotected and exposed constructed elements (El-Rayes and Moselhi 2001), by disrupting communications and/or blocking access to site locations (Alarcón *et al.* 2005), to cite but a few. Moreover, weather-related claims are a frequent source of dispute between contractors and project owners (Moselhi and El-Rayes 2002, Nguyen *et al.* 2010). It is not unusual that in the absence of agreement, unsettled claims can escalate into legal disputes and protracted litigation causing suspension of work for a longer period than the original abnormal weather episode itself (e.g. Finke 1990, Kumaraswamy 1997, Yogeswaran *et al.* 1998).

When categorizing the impact of weather, it is common to differentiate between foreseeable and unforeseeable weather (Tian and De Wilde 2011), as well as extreme and non-extreme (but generally combined) weather events (Jung *et al.* 2016).

Foreseeable weather is generally considered to encompass extreme adverse weather events that can impact the execution or exploitation of infrastructure unless precautionary measures are taken. Taking account of foreseeable weather is more frequently practised during the construction phase of special projects such as long, exposed bridges or high-rise buildings (Tanijiri *et al.* 1997, Jung *et al.* 2016). These types of projects normally have large budgets, and thus they are more likely to have resources for monitoring how and when on-site weather will cause changes to scheduled activities. Developments in sub-seasonal and seasonal weather forecasting have shown early promise too, but forecasts of acceptable quality still just span a maximum 10-d window (White *et al.* 2017).

However, despite advances in forecasting, there will always be an inherent uncertainty in a chaotic system such as the weather, which makes it difficult to always provide accurate forecasts. This is particularly true when considering extremes related to climate change (Sato *et al.* 2017).

Furthermore, whilst there are some construction activities that require forecast information for making good short-term decisions (e.g. whether to pour concrete today or tomorrow, or whether high winds will prevent work in exposed environments or at height), most resource-related operational decisions, and certainly all project planning, have to be undertaken anticipating weather beyond what current forecasting methods can predict. People (workers) have high manoeuvrability, but generally not the equipment, machinery, vehicles and special supplies that they employ. This is why this piece of research considers the applicability of climatology data drawn from historical

weather information as opposed to simple weather forecasts. This does not mean, however, that the importance of relevant and sometimes crucial short-term weather forecasting is not acknowledged.

The main aim of this paper is to propose a new approach for processing historical weather information from a construction-relevant perspective. Combinations of weather variables and intensities that affect the execution of construction activities have been analyzed and processed into a series of maps for construction managers.

From now on, this paper is structured as follows: the [Literature review](#) section includes an overview of the most relevant pieces of research proposing models of the interaction between weather and construction productivity. The [Materials and methods](#) section provides a comprehensive step-by-step description of the method proposed. Namely, in this section, the proposed model is first outlined; then how all the necessary weather data were extracted and processed; and, finally, how most weather variability can be captured by and reduced to sine wave curves. Next, the [Case study](#) section describes the application of the proposed method to the construction of a reinforced concrete building in the UK. The [Discussion](#) section provides further analyses and insights for both the case study considered and alternative potential applications. The [Conclusions](#) section summarises and highlights the contributions of this paper to both the scientific community and the construction practitioners. Finally, the [Supplemental online material](#) contains all the calculations, weather maps (the main research outputs generated in this study), as well as some programmable spreadsheets that allow performing weather-aware project scheduling calculations.

Literature review

General meteorological and climate research covering forecasting or retrospective analysis is significant and will not be reviewed here. Instead, the focus will be on two main areas. The first comprises the most recent models that have integrated the effect of weather in the planning and/or execution of construction works. The second is the particular combinations of weather variables and intensities that can produce significant impacts with regard to the execution of representative and frequent construction activities.

Overview of weather models for construction projects

Research on how weather impacts the execution of construction projects is plentiful. However, only

recently have quantitative models been developed for measuring the degree to which weather phenomena can cause a productivity decrease. A comprehensive sample of these quantitative models is summarized in Table 1.

Table 1 is first organized by type of construction project (first column) and second by chronological order of publication (second column). It can clearly be seen that almost all works have been published in the last 10 years, and that building projects in particular have

attracted the most attention. Furthermore, only one work proposes a forecasting model that uses live weather data retrieved from nearby stations to inform decisions regarding which construction activities to undertake in the short term. The remainder of the works containing forecasting models simply employs historical weather data. This suggests that there is a belief among construction researchers (or perhaps a lack of multidisciplinary input) that historical weather at nearby locations will be probabilistically or deterministically

Table 1. Sample of relevant research papers on the effect of weather on construction projects.

Project type	Publication year	Reference	Weather data source	Forecasting model	Activities analyzed	Weather agents
Buildings	1999	Thomas <i>et al.</i> (1999)	Historical (past) data	No	Steel structure delivery and erection activities	Temperature and snow
	2008	Jang <i>et al.</i> (2008)	Short-term (live) forecasts	Yes	Generic	Temperature and precipitation
	2008	Thorpe and Karan (2008)	Historical (past) data	No	Clearing and grubbing, excavation, foundations, structural erection, floors, interiors, roofs and HVAC	Temperature, snow, humidity and precipitation
	2010	David <i>et al.</i> (2010)	Historical (past) data	Yes	Generic	Solar radiation, temperature, humidity, wind
	2013	Dytczak <i>et al.</i> (2013)	Historical (past) data	No	Generic	Temperature and wind
	2013	Marzouk and Hamdy (2013)	Historical (past) data	Yes	Formwork	Precipitation and temperature
	2014	Shan and Goodrum (2014)	Historical (past) data	Yes	Steel structure	Temperature and humidity
	2014	González <i>et al.</i> (2014)	Historical (past) data	No	RC structures and finishing's (e.g. partition walls, windows, and doors)	Not specified
	2016	Jung <i>et al.</i> (2016)	Historical (past) data	Yes	Generic + core wall, steel frame, deck plate, RC, curtain wall	Solar radiation, temperature, wind and precipitation
	2016 2017	Li <i>et al.</i> (2016) Ballesteros-Pérez <i>et al.</i> (2017a, 2017b)	Historical (past) data Historical (past) data	No Yes	Steel reinforced bars Earthworks, formworks, concrete, steelworks, scaffolding, outdoor paintings and asphalt pavements	(Hot) temperature Temperature, precipitation, wind and electrical storms
Highways	2001	El-Rayes and Moselhi (2001)	Historical (past) data	Yes	Earthworks, base courses, drainage layers and paving	Precipitation
	2010	Apipattanavis <i>et al.</i> (2010)	Historical (past) data	Yes	Concrete and asphalt paving, structures, excavations and grading	Precipitation, air and soil temperature and wind
	2013	Chinowsky <i>et al.</i> (2013)	Historical (past) data	Yes	Generic	Temperature and precipitation
Pipelines	2011	Shahin <i>et al.</i> (2011)	Historical (past) data	Yes	Clearing and grading, trenching, bedding, pipe-fusing, laying-in, hydro testing, compaction and backfilling	Air and soil temperature, wind, humidity and precipitation
	2012	Duffy <i>et al.</i> (2012)	Historical (past) data	Yes	Grading, stringing, bending, welding, trenching, coating, backfill, clean-up	Temperature, wind, and precipitation
Tunnelling	2014	Shahin <i>et al.</i> (2014)	Historical (past) data	Yes	All tunnelling process, hoisting and muck car cleaning	Air and soil temperature and wind
Bridges	2015	Ballesteros-Pérez <i>et al.</i> (2015)	Historical (past) data	Yes	Earthworks, formworks, concrete and asphalt pavements	Temperature, precipitation, wind and electrical storms

repeated to some extent in subsequent years. It is also a common practice to use synthetically generated weather series for informing management decisions.

However, it is necessary to point out that Table 1 only includes studies with construction-oriented forecasting models. As mentioned previously, forecasting models in pure meteorology and other applied fields have not been considered here. The impact of weather on each field of application can help to identify the relevant weather variables, and ultimately demonstrates the value of better forecasting. Most construction projects, however, generally involve many disparate activities each of which is susceptible to different combinations of weather variables and intensities.

To date, most studies have focussed on very narrow sets of activities (last but one column in Table 1) and/or have considered a limited number of weather variables (last column). This generally constitutes a necessary simplification due to the difficulty of obtaining local (representative) data for a sufficient number of weather variables and from a sufficient number of locations. Moreover, the data available must also be sufficiently consistent (not much data missing), fine-grained (daily, hourly) and from a sufficient number of previous years to be useful.

The method proposed later can be considered a continuation of Ballesteros-Pérez *et al.*'s (2015, 2017b) research. As can be seen in Table 1, their models have already been adapted to two different types of projects (buildings and bridges), and have considered a varied and representative set of activities common to many construction projects (earthworks, formworks, concrete, steelworks, scaffolding, outdoor paintings and asphalt pavements). These models are of particular interest because they are two of the few covering extensive geographical areas (almost the whole of Chile and Spain, respectively), which means they can be used as general country-wide planning tools by governments and contractors alike.

However, the proposed method extends the scope of previous research in this area. Most previous studies (including those of Ballesteros-Pérez *et al.*) have required the use of either probabilistic or time series curves with many parameters or points. Some have also been developed to work with long series of discrete registers for modelling local weather. In contrast, the method proposed here only requires simple sine wave curves with only one, two or three parameters depending on the level of accuracy required. This is a significant advantage as the simplicity of the developed expressions means most construction managers will easily be able to use them in practice, with hardly any mathematical expertise.

In the next section, the selection of weather variables considered in this study will be justified as well as their relationship with a representative set of cross-project construction activities.

Combinations of weather variables affecting construction activities

The weather involves the confluence of multiple phenomena (wind, rain, heat, etc.) that quite often do not involve a clear correlation of occurrence with each other (Ballesteros-Pérez *et al.* 2017b). Studies analysing the seasonal variability of combinations of weather agents are quite scarce (Kim and Augenbroe 2012). However, it is precisely this weather variability (seasonal or not) that makes anticipating how weather will affect construction work difficult.

In this study, it is assumed that the impact of weather can be represented in a project schedule via activity duration extensions and, in some cases cost increases, and that weather-aware construction schedules can be useful tools for helping construction managers make better decisions.

The first stage is thus deciding which combinations of weather variables and intensities determine whether certain construction activities can be performed. The impact of a particular set of weather variables and intensities on an activity can be very different depending on the: construction technologies employed, equipment used, materials involved and/or procedures adopted; how exposed the construction site is; how persistently (consistently and/or repetitively) the weather is classed as unusual; what is considered the average (or normal) weather in the particular region (or country). However, it is still possible to choose a combination of weather variables that, under some common conditions (e.g. same country, similar construction technologies, materials and construction practices), can be considered as 'relatively representative' of the regional/industry standard. This study will consider the thresholds for the weather variables described in Table 2 as precluding the stated construction activities.

As noted, the combination of weather variables in Table 2 might not be appropriate for many countries or contexts. However, it is considered sufficiently representative for the UK which is where the proposed method will be applied later. Similar combinations of weather variables have also been considered recently by other authors (Ballesteros-Pérez *et al.* 2017a, 2017b) for both Spain and the UK.

By way of explanation for the values chosen, earthwork activities are more difficult to execute when the

Table 2. Weather variables and thresholds assumed to cause non-working days.

Weather variable (daily value)	Earthworks (E)	Concrete (C)	Formworks/scaffolding (F)	Steelworks (S)	Outdoor paintings (O)	Asphalt pavements (P)
Minimum temperature $\leq 0^{\circ}\text{C}$		x				x
Mean temperature $\leq 0^{\circ}\text{C}$	x			x	x	
Maximum temperature $\geq 40^{\circ}\text{C}$		x		x		x
Precipitation $\geq 1\text{ mm}$					x	x
Precipitation $\geq 10\text{ mm}$	x	x				
Precipitation $\geq 30\text{ mm}$				x		
Hail precipitation					x	x
Snow precipitation					x	x
Electrical storm			x	x		
Wind gusts $\geq 30\text{ knots}$		x	x	x	x	

ground is partially or totally frozen (Shahin *et al.* 2011, 2014) or when too much water causes a slope to become partially unstable (NCHRP 1978, El-Rayes and Moselhi 2001).

Concerning activities involving concrete, the minimum temperature must not drop below 0°C before it has hardened, otherwise it will microfracture (American Concrete Institute 1985). The temperature must also not rise above 40°C and/or the wind speed exceed 30 knots, or the concrete will dry out too fast when curing (American Concrete Institute 1985). In addition, the amount of extra water coming from rain, snow or hail must be small (e.g. 10 mm), otherwise the water/cement ratio will vary affecting the concrete's final strength and durability (NCHRP 1978, American Concrete Institute 1985).

Formwork and Scaffolding activities are affected in a similar manner by the weather. In particular, their execution is unsafe during electrical storms (due to the risk of electrocution) (Rogalska *et al.* 2006) and high winds (Nguyen *et al.* 2010, Marzouk and Hamdy 2013).

Steelwork activities are also sensitive to electrical storms and high winds (Irizarry *et al.* 2005), but in addition are affected by extremely high and low temperatures (Thomas *et al.* 1999) and excessive amounts of rain (particularly welding) (Thorpe and Karan 2008).

Outdoor painting activities can be difficult to execute when it is raining, snowing or hailing as when the paint is still fresh, extra water can decrease the effectiveness of the primer and/or lead to colour changes (Ballesteros-Pérez *et al.* 2015). Water-based paints can also lose their adherence if they freeze when drying. In addition, painting in windy areas is risky as painting equipment, like buckets, can be blown over or fall onto lower levels (Nguyen *et al.* 2010).

Finally, asphalt pavements are very susceptible to the addition of small quantities of water (in the form of rain, snow or hail) (El-Rayes and Moselhi 2001, Apipattanavis *et al.* 2010), and to extremely high and low temperatures (NCHRP 1978).

Materials and methods

Method outline

This section will describe a method for processing historical weather information from a construction-relevant perspective. The weather data employed is limited to inland stations, because the latter normally register more weather variables than at sea. The method involves three main stages.

The first stage involves gathering and analysing historical daily weather data from as many weather stations as possible. By 'analysing', we mean calculating the percentage of each day considered 'workable' in previous years, where workable implies that none of the weather variables exceeded the threshold values in Table 2 such that the completion of an activity would be prevented. More specifically, the analysis involves calculating percentages of workable days for every single day of the year (1–365), for each of the six construction activities [e.g. earthworks (E), concrete (C), formworks/scaffolding (F), steelworks (S), outdoor paintings (O) and asphalt pavements (P)].

The second stage involves fitting sine wave curves to the data for the percentage of workable days for all days of the year. Each type of activity and weather station require one sine wave curve, and then all of the parameters from the various sine wave curves for a particular activity can be represented on contour maps. These maps allow easy interpolation of the values of the sine wave parameters for a particular site when no weather stations are located nearby.

Finally, the third stage involves applying the necessary location-specific sine wave data to a construction schedule so that time (and cost) extensions can be anticipated. In this latter stage, it will be assumed, as in almost all previous models, that past weather and climate patterns will be repeated to some extent in the upcoming years for a given location.

The next two subsections include detailed descriptions of the first and second stages, respectively. The following section (Case study) will describe stage three, i.e. the application of the weather model to a project schedule.

Analysis of UK weather data

This subsection will detail and exemplify how calculation of the number of workable days was performed for the UK (England, Wales, Scotland and Northern Ireland) for the six generic types of construction activities described in Table 2.

First, daily weather data were retrieved from the UK Met Office (2018) databases, particularly from the MIDAS dataset. Data were extracted from only those weather stations with daily registers of maximum, minimum and mean temperature, rainfall and maximum wind gust, as well as snow, hail and thunder flags. Additionally, only weather stations that started registering these variables between 1986 and 1996 were selected for the sake of representativeness. Thirty years are the standard adopted by the World Meteorological Organization for analysing climatic patterns. However, we resorted to a minimum of 20 years coverage to increase the number of stations from 40 to 102, and because Vose and Menne (2004) proved that 20 years were quite likely to be beyond what is necessary for capturing interannual variability for construction works. In any case, even departing with 20–30 years nominally, in most cases, the meteorological equipment at each station had either malfunctioned and/or required periodic maintenance resulting in blank periods in the data.

Therefore, 102 stations were eventually considered from across the UK spanning 20–30 years, but with occasional (normally minor) data blank periods. The locations of these stations are shown in Figure 1 where they are marked using the UK Met Office (2018) codes from the MIDAS dataset.

It is worth highlighting that whenever at least one weather variable was not registered for a given day, that day was completely ruled out for that weather station. The reason for this was to avoid optimistic bias when assessing whether the day was workable (a day is more likely to be workable when fewer variables that might cause a day to be non-workable are considered).

The final cutoff criterion was whether the data from a given weather station for a particular type of construction activity had at least three complete registers for a given day (all weather variables registered) for at least half of the days (not necessarily consecutive) of the year. This filter ruled out two complete weather station registers from the initial 102, but also up to 48% of the weather stations for outdoor painting and asphalt pavement activities.

Nevertheless, with a minimum of 52 stations' historical registers per activity, there was a considerable amount of data to be processed. The number of weather stations included was much larger than in most of

the studies listed in Table 1, and generally many more complete years of data (around 23 on average per weather station) were analyzed. Complete calculations are available on the first Supplemental Online Material spreadsheet file for all stations and activity types.

The next step involved calculating the climatic reduction coefficients (CRC). A CRC, as defined by Ballesteros-Pérez *et al.* (2015), represents the percentage of each day in past years that was considered workable. This means that none of the relevant weather variables exceeded their threshold values from Table 2 for a given activity and weather station. Hence, the value of the CRC corresponds to the percentage, or per-unit value, representing the probability of a day being workable for a particular type of activity. A representative sample of CRC calculations for different weather stations and activity types (E, C, F, S, O and P) is shown in Figure 2. All CRC values can be found by activity type for all weather stations in the last six tabs of the same Supplemental Online Material spreadsheet.

Along with the CRC data (black lines) in Figure 2, two smooth curve fits are shown: a sixth-degree polynomial (seven parameters) in blue, and a sine wave curve (up to three parameters) in red. As can be seen, both curves fit the data similarly, meaning the sine wave curve represents a good fit with the CRC data even with substantially fewer parameters. Later, the loss of precision after having resorted to sine wave expressions will also be examined.

Reduction of weather variability to sine waves

As exemplified in Figure 2, sine wave expressions were fitted to all weather stations' CRC data for all types of construction activities. Sine waves, in this case, are mathematical expressions whose equations and parameters are of the form:

$$y = \text{CRC} = K + A \cdot \cos(2\pi f(x/365 - \phi)) \quad (1)$$

where:

CRC: climatic reduction coefficients: (E, C, F, S, O and P). Percentage of workable days for each day of the year (x).

x : day of the year (days 1–365). In leap years, the 29th February is considered as $x = 59.5$.

K : vertical shift (in per unit). Approximately corresponds to the geometric mean of the annual CRC values.

A : amplitude (in per unit). Approximately corresponds to the maximum positive and negative average oscillation of the CRC values with respect to K .

f : frequency. This was set at 1 so that 365 d corresponded to one complete oscillation.

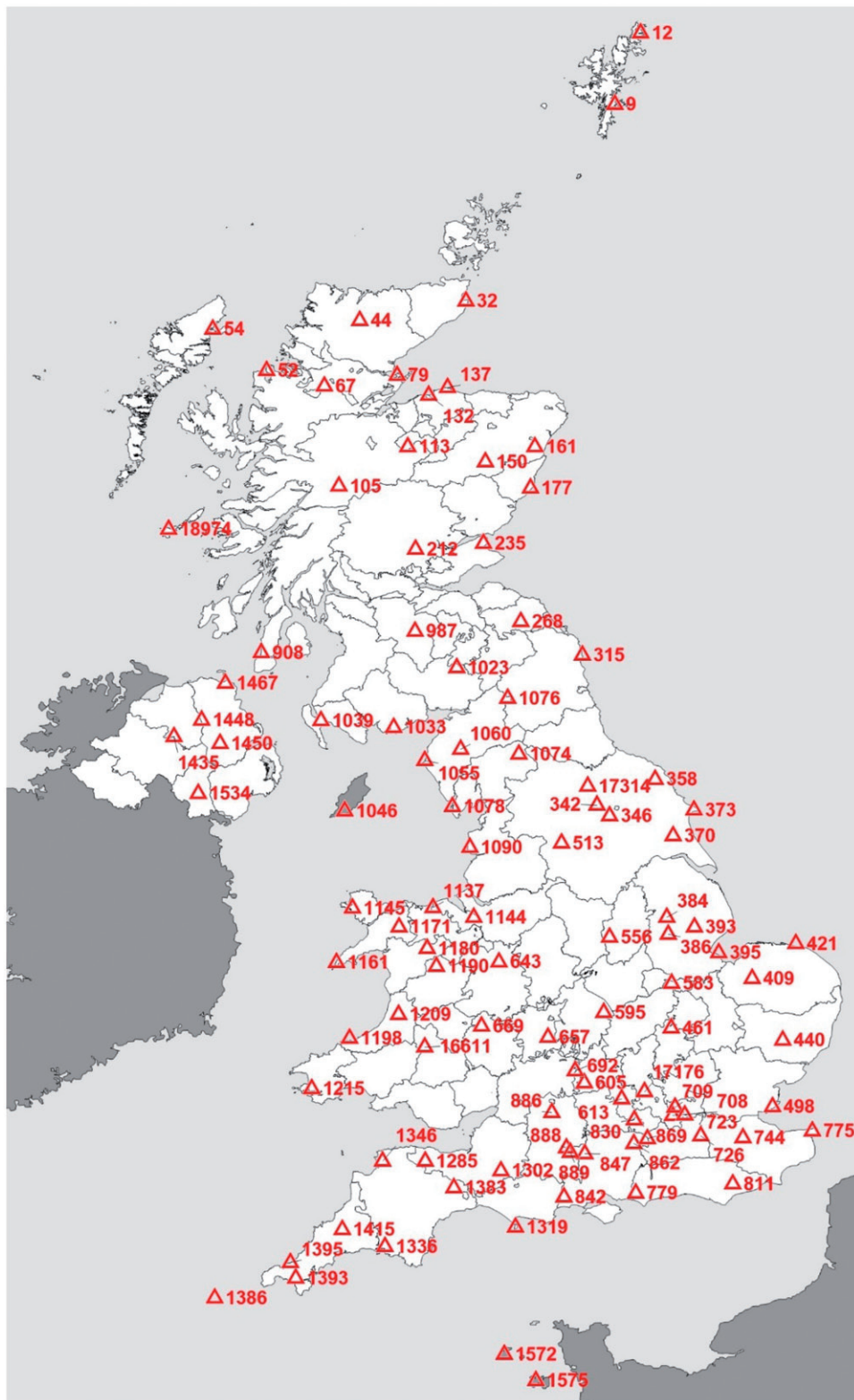


Figure 1. Locations of weather stations used for the analysis.

φ : phase shift (in per unit). Corresponds to the day of the year (but expressed in per unit) when the sine wave reaches its maximum value (optimum weather conditions). This is true because expression (1) has been built using a

cosine, instead of a sine. However, unless multiple waves are compared, cosine waves are also named sine waves. We will follow the same terminology here and refer to expression (1) as a sine wave then.

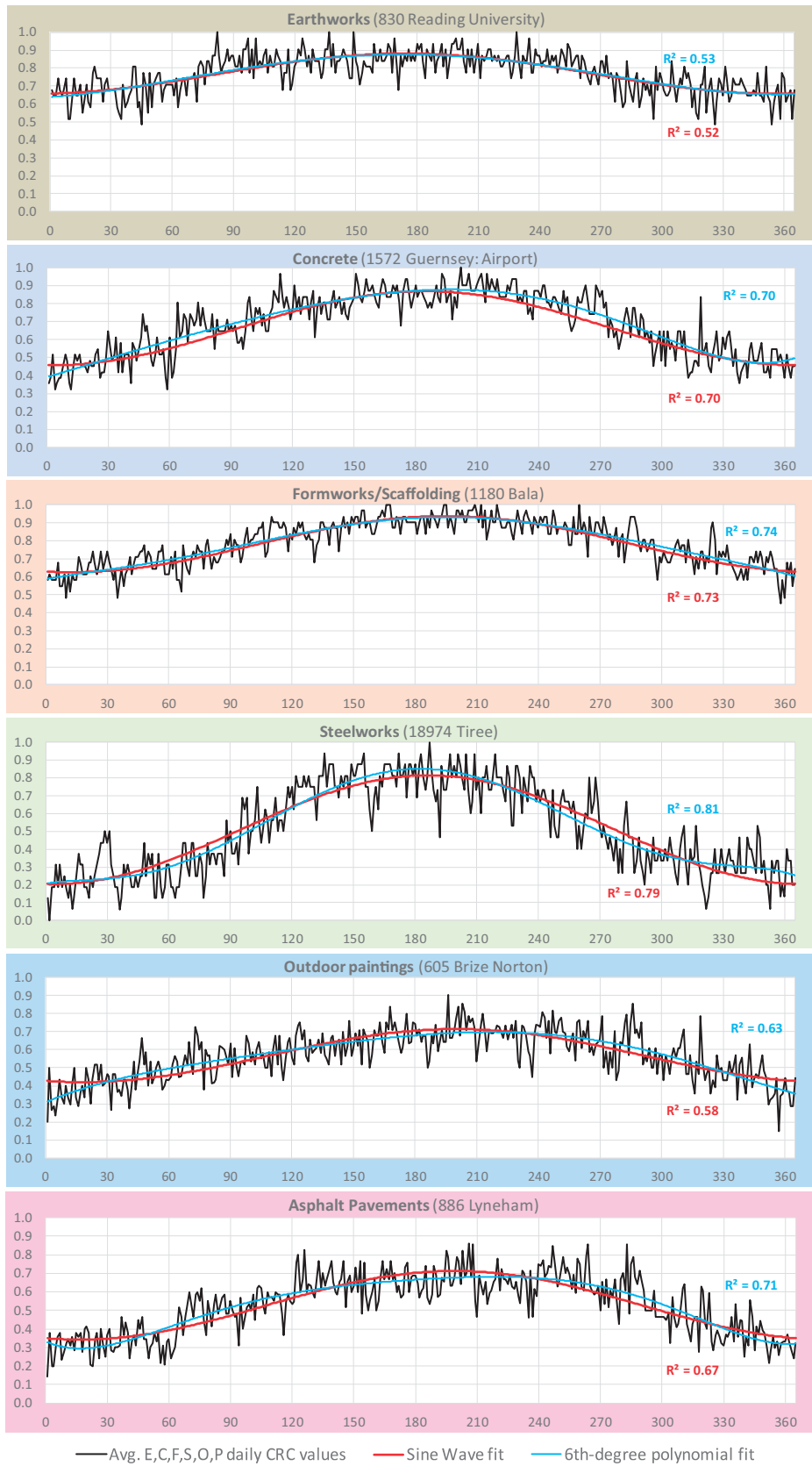


Figure 2. Examples of average daily CRC calculations for all construction activities.

Hence, each sine wave curve has three free parameters (K , A and φ). The values of these parameters were obtained by minimizing the least squares between each sine wave curve and its respective CRC data for each CRC data series (i.e. for each weather station and construction activity type).

A summary of the final (K , A and φ) parameter values can be found on the second tab of the [Supplemental Online Material](#) spreadsheet mentioned above. Details of the errors associated with the sine wave expressions can be found in the first tab of the same file. Errors between the CRC and the sixth-degree polynomial fits are also available for the cases where there were enough data.

However, a series of K , A and φ values are not necessarily immediately useful unless the construction site is geographically close to one of the weather stations. Therefore, a series of maps for each sine wave parameter and type of activity was developed. An example set of maps for the three parameters (K , A , and φ) corresponding to formworks/scaffolding activities is shown in [Figure 3](#).

These contour maps were created with Surfer v.14[®] (Golden software, CO, USA) from gridded data by implementing a Kriging interpolation method. This interpolation method was invented in the 1950s by the South African geologist Danie G. Krige for predicting distribution of minerals. However, it was mathematically formalized by the French engineer Georges Matheron in the 1960s (Matheron 1969). For statisticians, the Kriging interpolation method is also known as Gaussian process regression. This as it is a method of interpolation for which the interpolated values are modelled by a Gaussian process governed by prior covariances. With only mild conditions on the priors, Kriging interpolation gives the best linear unbiased prediction of intermediate values, which is why this method was used here. Maps for the other five activities are included in the PDF file in the [Supplemental Online Material](#).

Furthermore, one of the main aims of this study was to develop a series of expressions that were not just as representative as possible, but also as simple as possible. Therefore, after obtaining the original K , A and φ values for all weather stations and type of activity, the values were represented by type of construction activity graphically as shown in [Figure 4](#). The intention was to determine whether the amplitude A and/or the phase shift φ could be expressed as a function of the vertical shift K in order to reduce the number of parameters in [Equation \(1\)](#) and obtain the simplest expressions possible.

Quite surprisingly, the amplitude A exhibited a degree of correlation with K . This is probably due to some common boundary conditions for the two parameters. For example, when K has its lowest ($K=0$) or highest ($K=1$) value, A must equal zero ($A=0$) as there is no oscillation possible. Similarly, A is expected to approach its maximum value when K is approximately equal to 0.5. Overall, this means that a single-parameter quadratic expression crossing the points ($K=0, A=0$) and ($K=1, A=0$) should model the correlation between the two variables. That quadratic expression corresponds to $A=a_i(K-K^2)$, and the best-fit values for a_i for the six types of activities are represented on the left hand of [Figure 4](#).

In contrast, there was little correlation between K and φ ; this was because φ does not vary significantly with K or the station location. This can be checked easily as the value of φ lies within a relatively narrow vertical band. Hence, it is possible to assume with little error, that φ is a constant for each type of activity. The two values of this constant (for earthworks and for all other activities) are given on the right side of [Figure 4](#).

To summarise, the original three-parameter (3-p) sine wave expression can be reduced most of the time to a 2-p, or even a 1-p expression, by assuming that K is the only free parameter. In other words, A can be replaced by a quadratic expression which is a function of K ($A=a_i(K-K^2)$) and φ can be assumed to be constant.

The remaining step involves checking whether the 3-p, 2-p and 1-p sine wave approximations generate sufficiently small errors in comparison to the original CRC data series. Details of the calculations can be found at the bottom of the second tab in the [Supplemental Online Material](#) spreadsheet and are summarized in [Table 3](#).

[Table 3](#) contains the mean squared errors (MSE), mean absolute errors (MAE) and mean absolute percentage errors (MAPE) for the three sine wave approximations for each type of construction activity. It also includes the average squared, absolute and percentage deviations between neighbour CRC points from consecutive days which reflects the small scale variability or jaggedness of the CRC curves. It can not only be seen from the data in [Table 3](#) that the errors for the 2-p and 1-p sine waves are not significantly larger than the errors for the 3-p versions, but also that the errors remain below the deviations between neighbour points. This means that the simplified 2-p and 1-p sine waves closely reflect the CRC curves almost all of the time, and are not too dissimilar to the 3-p sine waves.

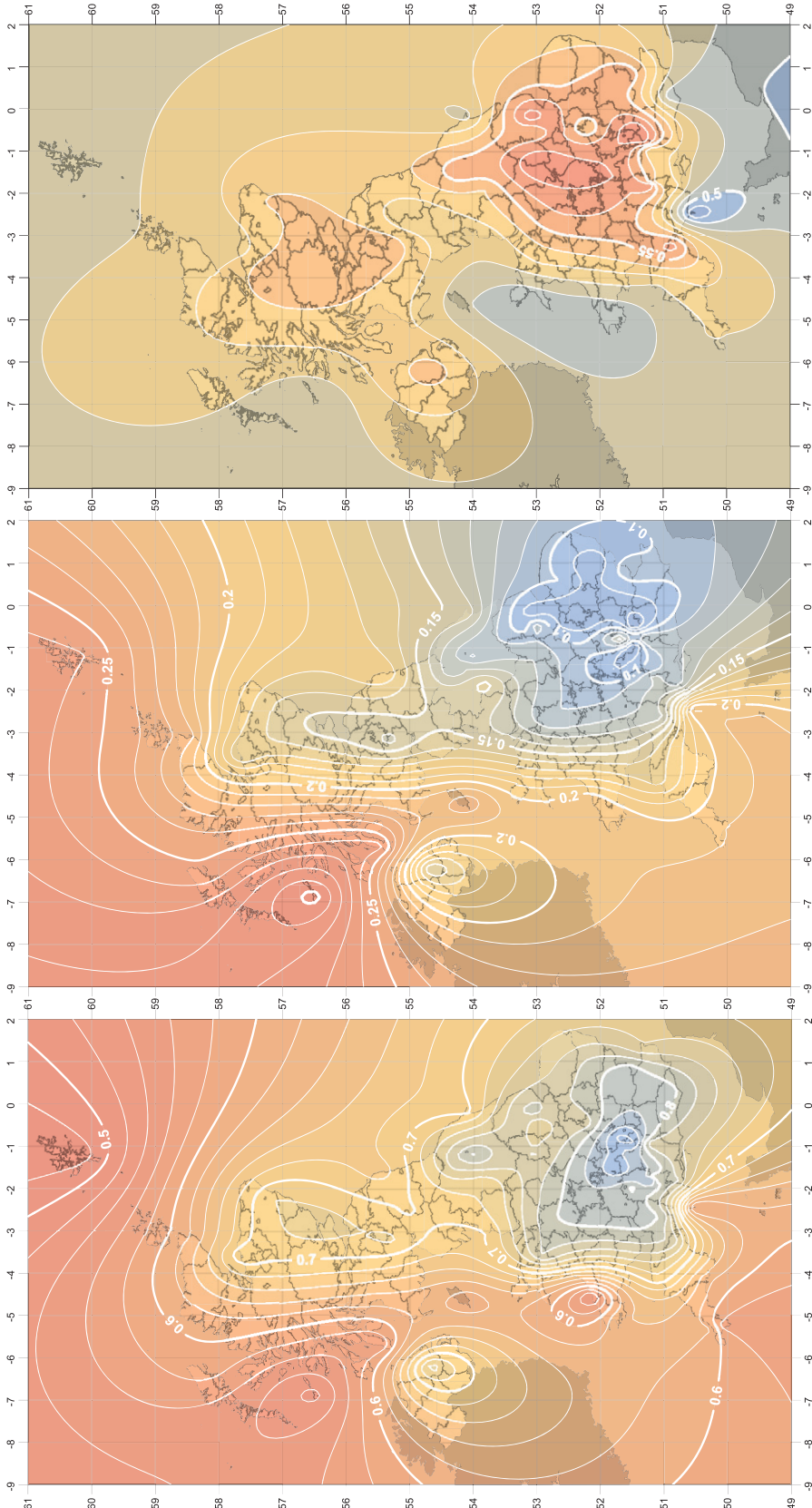
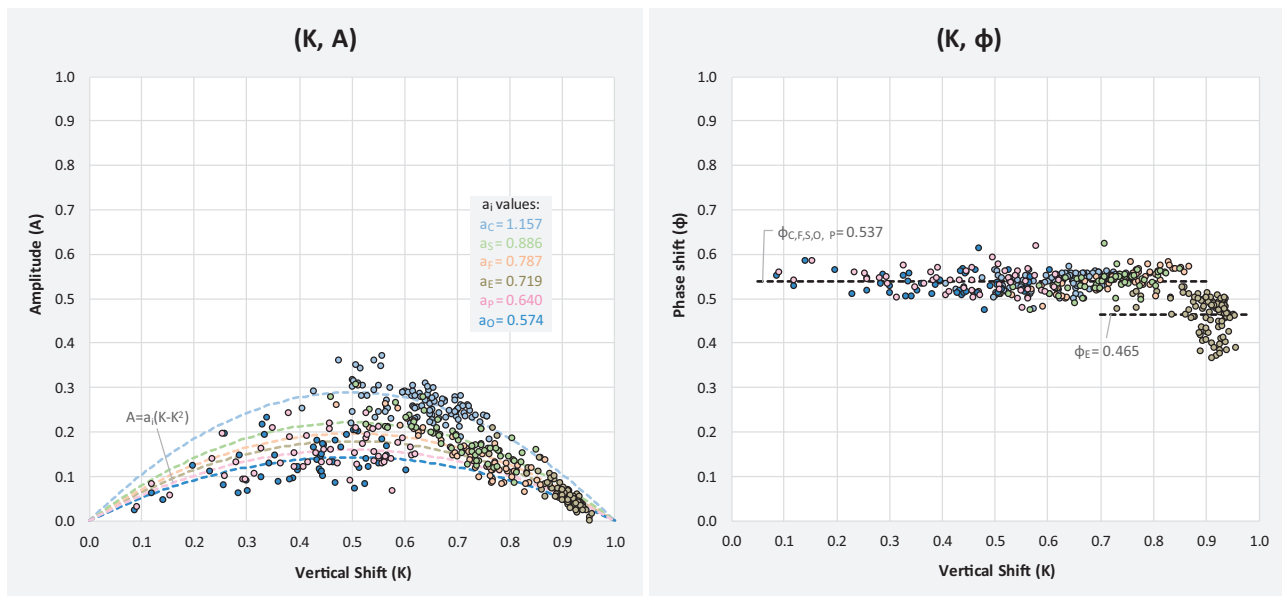


Figure 3. Example maps for vertical shift K (bottom), amplitude A (middle) and phase shift φ (top) for formworks/scaffolding activities in the UK.



○ Earthworks (E) ○ Concrete (C) ○ Formworks/Scaffolding (F) ○ Steelworks (S) ● Outdoor paintings (O) ○ Asphalt Pavements (P)

Figure 4. Plots of K , A and ϕ values with regression expressions assumed.

Table 3. Errors in CRC estimates.

Data	Error	E	C	F	S	O	P	Average
3-p sine waves (K , A and ϕ are free)	MSE	0.004	0.017	0.012	0.016	0.017	0.017	0.01
	MAE	0.050	0.076	0.083	0.095	0.096	0.097	0.08
	MAPE	0.058	0.140	0.124	0.148	0.276	0.261	0.17
2-p sine waves (K and A are free, $\phi = \text{constant}$)	MSE	0.005	0.010	0.013	0.017	0.017	0.017	0.01
	MAE	0.051	0.077	0.084	0.096	0.097	0.098	0.08
	MAPE	0.058	0.143	0.126	0.150	0.278	0.263	0.17
1-p sine waves (K free, $A = f(K)$ and $\phi = \text{constant}$)	MSE	0.005	0.010	0.013	0.017	0.018	0.018	0.01
	MAE	0.052	0.080	0.086	0.098	0.100	0.100	0.09
	MAPE	0.059	0.146	0.128	0.151	0.285	0.268	0.17
Deviations between neighbour data points (consecutive CRC values)	MSE	0.006	0.012	0.018	0.023	0.023	0.024	0.02
	MAE	0.057	0.084	0.098	0.108	0.112	0.114	0.10
	MAPE	0.067	0.168	0.157	0.184	0.337	0.322	0.21

Finally, from the average R^2 values from all weather stations by type of construction activity (see the Excel spreadsheet with summary of all regression calculations in the [Supplemental Online material](#)), it can be claimed that overall, the proposed sine waves capture between 28% (at worst, for earthworks) and 79% (at best, for concrete) of the average weather variability, and this is accomplished with reasonably simple mathematical expressions suitable for use by construction managers during project planning. The final stage is to implement the developed expressions in a real project, which is the purpose of the next section.

Case study

An example of how the sine waves can be used during construction scheduling is contained in this section. The schedule proposed here represents the construction of

a fictitious simplified three-storey reinforced concrete building. It consists of 24 activities arranged under three work packages, as shown in [Figure 5](#).

[Figure 5](#) represents a weather-unaware schedule, or a schedule in which the activity durations have been calculated without considering the potential impact of the weather. The schedule represented in [Figure 5](#), like the following schedules calculated later, has all been generated assuming unlimited resources. The way this weather-unaware schedule can be transformed into a weather-aware schedule is relatively simple.

The first step consists of identifying which type of activity (E, C, F, S, O or P) each schedule activity resembles the most. These allocations are represented by the different coloured bars in [Figure 5](#). Activities with grey bars are not weather-sensitive (because they are executed indoors, for instance) and for which the duration will not change when the weather is considered.

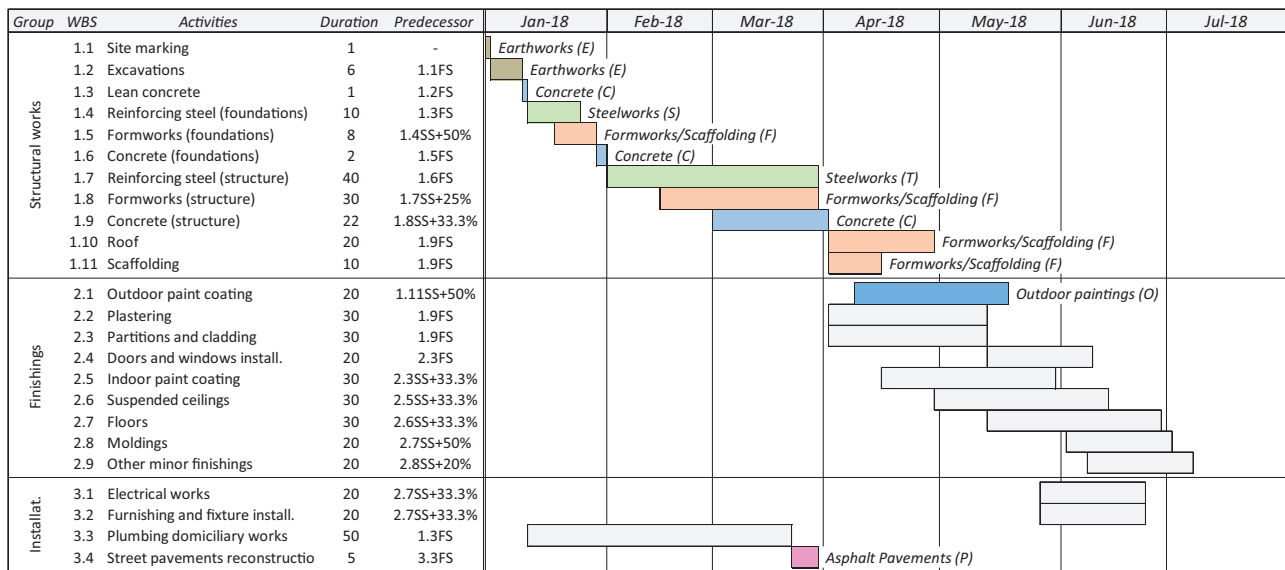


Figure 5. Construction schedule for a simplified three-storey reinforced concrete building.

The second step involves calculating how much longer each weather-sensitive activity will take to complete once the effect of the weather is included. For this, the corresponding sine wave expression for each activity is required. The choice of sine wave expression depends on the type of activity (E, C, F, S, O or P) and the location. The appropriate values of K , A and ϕ for each sine wave can be obtained from maps like the ones described in Figure 3, or via an automated (and far quicker) process from a grid data file using the activity (or project location) coordinates. Grid values for all three parameters for the six types of construction activities can also be found in the third tab of the Supplemental Online Material spreadsheet.

The third and final step comprises taking both the (one, two or three) parameters for each sine wave curve and the start date of each activity and adding up the CRC values from the sine wave expression as x (the day of the year) increases. Variable x thus takes its first value from the activity start date and continues to increase until the sum of the generated CRC values is equal to the original activity duration. This is equivalent to considering that the sum of the fractions of productivity on consecutive days will equal the originally defined duration of the activity (the one calculated assuming that all days would be 100% workable). The last day for which variable x is added to the sum will correspond to the finish date of the new (weather-aware) activity duration. This process can be repeated for all project activities in chronological order of their start dates until all the activity durations have been revised.

Having defined the calculation process, the total duration of the building project can be found taking

into consideration the weather. This has been done for all major cities in the UK in order to find out how significant, but also how different, the impact of the weather can be in different locations.

It is initially worth noting that the original (weather-unaware) project duration was 186 d, which is a little more than 6 months. In the analysis, working days are considered to be Monday to Friday only, but the total duration calculated includes Saturdays and Sundays. No extra holidays have been considered.

The reason why this specific project configuration has been adopted is because it represents the most challenging situation for the 3-p, 2-p and 1-p sine wave approximations. Half-year projects are generally the ones that experience the (proportionally) greatest weather-related variability; longer projects can offset this variability through summer and winter. Moreover, including non-working days (in this case Saturdays and Sundays) means there are bigger deviations possible in project duration estimates with the 1-p, 2-p and 3-p sine waves as every 5 d, two more are added. The predicted project durations are shown in Figure 6.

Interpretations of Figure 6 are manifold so only the most important will be highlighted here. First, it is necessary to state using the 3-p sine waves and the actual series of CRC values produced exactly the same estimated project durations for all cities and for all project start dates. This is not necessarily a surprise and the differences between these approaches may only be noticeable if the initial project duration is of the order of a few days, instead of a few months.

The duration estimates calculated using the 3-p sine waves indicate that the weather is likely to cause an extension to the original (weather-unaware) 186-d

Project baseline dur. = 186 days	3-param. Sine Waves (exact calculations)			2-param. Sine Waves (good approximations)			2-param. Sine Waves (quick approximations)			1-param. Sine Waves Absolute Errors				
	City (UK)	Region	Year:ave.	Min.dur.	Max.dur.	Day:Min	Year:ave.	Min.dur.	Max.dur.	Day:Min	Year:ave.	Min.dur.	Max.dur.	Day:Min
Aberdeen	Scotland	232.7	198	272	129	265	232.8	218	241	122	272	20	31	7
Aberdeen	Scotland	224.6	194	257	134	270	221.8	207	236	134	291	8	21	0
Armagh	N. Ireland	255.0	211	304	116	244	252.0	215	287	120	257	3.0	4	13
Bangor	Wales	216.5	192	265	143	282	214.2	201	227	120	300	2.3	9	18
Bath	England	229.2	197	263	136	285	225.0	213	237	135	276	4.1	16	23
Belfast	N. Ireland	214.9	193	242	113	292	212.9	204	223	114	297	2.0	11	19
Birmingham	England	230.2	194	266	127	279	226.4	207	242	106	272	3.8	13	24
Birmingham	England	213.7	193	238	120	279	212.7	201	227	127	300	0.9	8	11
Brighton & Hove	England	215.8	192	245	141	286	213.4	201	224	113	289	2.4	9	21
Bristol	England	216.9	193	244	127	292	215.1	205	224	143	284	1.9	12	20
Cambridge	England	214.6	194	236	127	284	213.9	205	224	123	290	0.7	11	12
Canterbury	England	216.9	192	248	142	279	214.7	200	229	134	286	2.2	8	19
Cardiff	Wales	217.4	226	308	71	220	213.0	239	307	40	188	1.6	13	31
Cardiff	Wales	212.0	193	235	106	292	210.9	201	220	113	286	1.1	15	7
Chelmsford	England	218.5	193	250	120	298	216.3	206	228	120	278	2.2	13	22
Chester	England	217.1	194	243	134	271	215.5	205	227	128	279	1.6	11	16
Chichester	England	215.6	192	237	120	297	211.1	201	222	113	305	1.4	9	15
Coventry	England	216.7	193	244	127	284	215.0	204	227	106	272	1.7	11	17
Dundee	Scotland	231.8	196	276	130	258	227.5	215	242	106	306	4.3	19	34
Durham	England	233.9	197	272	135	276	228.2	213	243	113	293	5.7	18	29
Edinburgh	Scotland	238.1	197	280	135	258	231.0	213	251	106	292	7.1	16	29
Ely	England	219.0	194	248	127	279	216.9	206	229	156	288	2.1	12	19
Exeter	England	224.8	194	258	127	285	222.4	205	238	128	289	2.4	11	20
Glasgow	Scotland	255.4	201	294	113	251	246.7	221	265	99	230	8.6	20	29
Glasgow	Scotland	215.2	192	243	148	291	212.9	201	224	127	299	2.3	9	20
Hereford	England	215.3	192	244	113	283	212.9	201	224	127	299	2.3	9	20
Hereford	England	250.1	197	300	136	256	239.7	215	263	134	272	10.3	18	37
Hereford	England	219.4	197	248	134	293	217.8	211	227	93	272	1.6	14	21
Kingston-upon-Hull	England	231.7	200	265	113	258	227.5	214	242	107	278	4.2	14	23
Leeds	England	230.0	200	266	99	247	222.1	208	236	134	286	3.1	14	24
Leeds	England	215.1	193	241	127	293	213.5	204	224	99	293	1.6	11	17
Lichfield	England	215.8	193	243	120	286	213.9	204	224	129	285	1.9	11	19
Lincoln	England	217.8	197	243	131	278	216.0	206	227	127	286	1.5	9	16
Lisburn	N. Ireland	223.5	194	255	127	279	221.1	208	234	141	272	2.5	14	21
Lisburn	N. Ireland	221.1	194	251	120	269	218.9	211	229	122	293	2.2	17	22
Liverpool	England	211.3	193	234	106	279	210.2	200	221	100	278	1.1	7	13
Liverpool	England	239.0	200	278	120	270	233.3	217	251	108	269	5.7	17	27
Manchester	England	225.6	194	260	127	276	222.0	207	237	113	278	3.6	13	23
Manchester	England	234.6	199	272	141	265	229.2	215	243	134	278	5.4	16	29
Newcastle-upon-Tyne	England	215.8	191	245	156	286	213.4	200	228	120	306	2.4	9	17
Newport	Wales	223.3	194	255	127	272	220.8	208	234	134	293	2.5	14	21
Newry	N. Ireland	220.5	198	246	141	270	219.1	211	228	122	265	1.4	13	18
Norwich	England	217.9	193	245	134	286	216.2	205	228	136	271	1.7	12	17
Nottingham	England	211.6	191	237	149	278	209.3	199	221	108	292	2.3	8	16
Oxford	England	235.1	194	276	134	251	228.2	213	244	108	290	6.9	19	32
Oxford	England	220.2	198	248	136	300	218.4	208	229	141	284	1.8	10	19
Peterborough	England	235.7	201	272	127	271	233.1	219	249	102	265	2.6	18	23
Plymouth	England	218.6	194	246	120	269	216.5	205	228	120	278	2.1	11	18
Portsmouth	England	229.2	199	265	136	270	225.8	213	239	113	291	3.3	14	26
Preston	England	229.3	194	259	120	275	225.4	208	238	113	221	3.9	14	21
Ripon	England	225.3	194	260	127	271	222.1	208	236	134	286	3.1	14	24
Salisbury	England	224.0	193	251	113	255	219.3	203	232	131	241	4.7	10	19
Sheffield	England	220.5	193	251	127	278	217.8	205	230	120	270	2.7	12	21
Sheffield	England	218.7	193	249	106	278	216.2	205	229	120	284	2.5	12	20
Southampton	England	212.1	193	236	106	285	210.7	201	220	106	279	1.4	8	16
St Albans	England	218.3	193	244	114	272	216.1	205	227	129	279	1.2	12	21
St Albans	Wales	239.0	204	278	113	256	235.8	221	250	113	263	3.2	17	28
St David's	Wales	245.9	198	285	141	271	236.5	214	252	134	268	9.4	16	33
Stirling	Scotland	220.0	193	252	120	279	217.5	206	230	134	285	2.5	13	22
Strake-on-Trent	England	233.5	199	271	136	270	228.4	215	243	120	291	5.1	16	28
Sunderland	England	225.6	194	258	127	284	224.4	207	237	134	285	3.2	13	21
Swansea	Wales	241.0	204	280	129	270	237.9	221	255	121	265	3.1	17	25
Truro	England	228.7	194	262	120	258	226.8	208	243	92	209	1.9	14	19
Wakefield	England	217.2	192	249	141	285	214.7	204	227	121	300	2.5	12	22
Wells	England	211.3	193	234	106	279	210.2	200	221	100	278	1.1	7	13
Westminster	England	218.5	193	245	106	277	214.9	204	228	120	306	3.5	11	17
Winchester	England	216.3	193	244	113	284	214.1	204	224	117	294	2.2	11	20
Wolverhampton	England	214.4	192	242	149	292	212.1	201	223	127	305	2.3	9	19
Worcester	England	287.3	262	313	72	244	287.8	267	308	12	160	0.4	5	60
York	England	225.7	196.7	257.1	66	242	227.8	208.0	236.6	12	150	3.0	12.4	20.7
Average		225.7	196.6	257.2	66	242	227.8	208.0	236.6	12	150	3.0	12.4	20.7
Increase (vs. 186 days)		21.4%	5.8%	38.2%	0.1	0.6	19.8%	12.4%	27.2%	0.1	0.6	6.0	14.1	15.2

Figure 6. Predicted average, minimum and maximum project durations for the building project by UK city.

project duration by an average of 21.6%. However, this duration increase may be as large as 38.3%, or as small as 5.7%, depending on the start date. Therefore, if a project schedule was managed weather-wise (e.g. by carefully choosing the best project start date), average project durations could be reduced by $21.6 - 5.7\% = 15.9\%$. Analogously, time proportional costs, like indirect and overhead costs, could also be reduced.

With the 2-p sine wave approximations, it can be seen that deviations in predicted project durations are almost always below 1 d (see the first three columns of the 2-p Sine Waves Absolute Errors). Identifying the optimum and worst project start days with regard to minimizing and maximizing project duration also on average remain below 1 week (see last two columns of the 2-p Sine Waves Absolute Errors). This is a very good approximation considering the simplicity of the 2-p expression being used to model an entire year day-by-day. Moreover, these predicted errors are the greatest over the year, and for the remainder of the year, deviations are much smaller.

In contrast, the 1-p sine wave curves produce significantly poorer approximations. This being said, average project duration errors remain below 3 d on average (see first columns of the 1-p Sine Waves Absolute Errors) which is in reality small and an upper bound. Projects longer than 6 months and/or those without non-working days will generally have less error. The shortest and longest project duration estimates, as well as their associated start dates err on average by less than 2 and 3 weeks, respectively (see the second and third columns of the 1-p Sine Waves Absolute Errors). In practice, these would not be considered bad estimates, especially as they come from such simple expressions with just one parameter. Moreover, similarly to the 2-p sine wave estimates, the errors quoted represent the largest possible errors and with longer projects or different project start dates, they are significantly reduced.

Discussion

The case study above shows how the sine waves proposed can be used with a straightforward approach to calculate individual activity and total project durations. Clearly, the possibility of calculating how long each activity will last depending on the start date and the location opens the door for further operational research applications. For example, it would be possible to analyse (a) how best to reduce project durations and costs when multiple projects have to be executed and their order can be modified; (b) how best to arrange non-critical activities to minimise

durations and/or costs; and (c) how to select the best project location if that was a feasible option.

The proposed sine waves can also be applied with a stochastic approach instead of the discrete approach used in the case study here. In this case, each CRC daily value would be either 0 (workable day) or 1 (non-workable day), where the probability of the value being 0 or 1 would depend on the CRC calculated by the sine wave expression for each day. The CRC data series represent proportions of workable days from the past, but they can also be understood as 'probabilities' of a day being workable. This means that Monte Carlo simulations can be very easily implemented and used to calculate, through multiple iterations, a wide range of (probabilistic) project durations. This application, despite very interesting, goes beyond the aim of this paper, but, for the sake of promoting further research, a programmable spreadsheet has been included as [Supplemental Online material](#) which performs the Monte Carlo simulations described above.

Furthermore, the sine waves can also be employed in weather-aware schedules for calculating corresponding weather-unaware activity durations. This kind of forensic analysis would be of interest when dealing with weather-related claims. In this case, the actual activity durations (from the as-built schedule) have necessarily already been affected by the weather. Therefore, calculating the CRC values for each activity and adding them up from the actual activity start date until its finish date are all that is needed. Later, if an extended analysis is required, it would be possible to submit the calculated (weather-unaware) activity durations to Monte Carlo simulations. These simulations would provide the probabilistic project durations curve, from which it would be possible to determine the percentile to which the actual (as-built) schedule duration corresponded. This percentile would indicate whether some form of time and/or cost compensation would be appropriate, helping to mediate negotiations between contractors and clients. Again, despite giving more details about this application exceeds the aim of this paper, another programmable spreadsheet that performs 'forensic' weather scheduling analyses has been appended as [Supplemental Online material](#).

Finally, although the sine wave method proposed may prove useful in many applications, it should be pointed out that it does have some limitations, even disadvantages. Regarding disadvantages, any project manager who is aware of the Parkinson's law (project work expands to fill all the available time) will know that allowing for increased activity durations (due to weather or anything else) might lead to lower productivity levels. This productivity decrease might be caused by resources

being more relaxed (on believing that they have more time than needed) or even by intentionally delaying the actual start dates due to the Student's syndrome (delay to start working on a task until it becomes really urgent). A nice case explaining how pervasive these two phenomena can be for project progress can be found in Vanhoucke (2012, p. 188–189).

Then, the method proposed here anticipates longer activity durations, but that does not mean the resources will have extra time to work on them. They will have exactly the original planned time (because they will not be able to work during some days due to adverse weather conditions). It is the project manager's responsibility to raise awareness on this issue and handle the resources as effectively as possible. Otherwise, further delays will occur.

However, concerning the proposed method limitations, the curves require data from as many weather stations as possible for improved accuracy and to make up for data sets that are not sufficient quality. This is not a problem in a country like the UK where weather stations are widespread and the data available spans many years. However, it could be an issue in other countries where there are significantly fewer and/or newer stations.

Moreover, the sine waves correspond to weather and thus workability at ground level (measurements taken at a height of 10 m). This means that for tall structures and/or for projects executed at sea, the curves may not be representative at all. Similarly, for projects located in very unusual and/or isolated regions where the climate is significantly different from nearby areas, the proposed sine wave curves may prove unrepresentative too.

However, there are many applications where the proposed sine waves will be more than sufficient, particularly as they are based on extremely simple mathematical expressions and allow for highly customisable combinations of weather variables.

A last cautionary note must be given before proceeding to the [Conclusions](#) section. On developing the case study, only deterministic scheduling analyses have been implemented. It is well known that, due to the Merge event bias¹ being neglected, deterministic schedules tend to underestimate the project duration (Ballesteros-Pérez 2017). Stochastic analysis has been intentionally not considered here for the sake of comparing homogeneous scheduling results (an original single weather-unaware deterministic schedule versus the remaining weather-aware, but also deterministic, schedules). This has allowed us to gauge the relative duration increases that are to be expected when introducing the weather factor. But also avoiding other sources of

potential bias like activity duration variability present in the original weather-unaware schedule. Finally, the case study developed consisted of a schedule with very few activities in parallel. This made the potential project duration underestimations a very minor cause of concern in this occasion. For future scheduling analyses, though, Monte Carlo simulations like the ones that can be performed in the spreadsheets included as [Supplemental Online material](#), are recommended.

Conclusions

Construction projects involve multiple weather-sensitive activities that frequently cause significant project delays and economic losses for both contractors and project owners. A significant proportion of infrastructure-related activities (from construction to operation and maintenance) are highly weather-sensitive, as they are mostly performed outdoors. This weather sensitivity, however, varies according to the nature of each activity, as well as the location and season in which they are carried out. Furthermore, different activities are susceptible to different combinations of weather variables (e.g. temperature, rain and wind) and their intensities.

Quantitative research on the influence of weather on construction productivity is scarce, predominantly less than 10 years old, and focuses mostly on building construction. Therefore, the main aim of this paper was to propose a method that allows construction industry professionals to plan in the medium- and long-term (beyond 2 weeks) considering the seasonal variation of weather. The method proposed is not limited to a small number of weather variables, nor to small geographical areas, and allows for many types of project activities to be considered.

The major contribution of this research is the development of a series of sine wave expressions that model quite closely the average probability of a day being workable for a particular type of activity. The curves also allow a planner to anticipate how much longer a project activity will take to complete as a consequence of the weather. The proposed calculations can cover all days of the year, and by selecting appropriate combinations of weather variables, can be defined for different types of activities and projects. Moreover, the expressions can be implemented with either one, two or three parameters depending on the degree of accuracy required.

Most construction projects comprise hundreds (sometimes thousands) of weather-sensitive activities which interact through a precedence network (e.g. certain activities must be completed before others can start). Ascertaining the weather sensitivity of a whole project requires combining the weather's impact on

multiple activities and determining the ensuing effect on the overall project duration.

In this paper, six frequent and standard construction activities were defined and the weather variable combinations and intensities commonly accepted as preventing them from being executed were justified. Using data from 102 weather stations and applying the relevant constraints, sine wave expressions corresponding to the six types of construction activities were calculated.

A case study involving the construction of a reinforced concrete building was used to demonstrate how these sine waves can be applied in the prediction of project durations. The findings from the case study indicate that UK weather can extend building project durations, on average by 21%. Furthermore, planning to minimise potential weather-related delays can lead to average project duration reductions of 16%, with associated indirect and overhead cost reductions.

Finally, some limitations and further applications of the proposed sine wave expressions were discussed. Among these applications, the use of the sine waves for stochastic weather-aware scheduling and in dealing objectively with weather-related claims is the most relevant. However, it is likely that many other applications of this research will be found in the future. Finally, to facilitate use of the model, the majority of the data analysis, results (contour maps of the UK), and programmable spreadsheets for performing both deterministic and stochastic project scheduling calculations have all been included as [Supplemental Online Material](#).

Note

1. Actually, the merge event bias is nothing but a special case of Jensen's inequality. This, as the maximum of the average durations of multiple activities which are performed in parallel is always equal to or lower than the average duration of the maximum of such activity durations.

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