Concrete Construction: How to Explore Environmental and Economic Sustainability in Cold Climates

Shiwei Chen 1, Weizhuo Lu 2, Thomas Olofsson 3, Mohammad Dehghanimommadabadi 3, Mats Emborg 3, Jonny Nilimaa 2, Yaowu Wang 1 and Kailun Feng 1*

1 Department of Construction Management, Harbin Institute of Technology, No. 13, Fayuan Street, Harbin 150001, China; shiwei.chen@ltu.se (S.C.); ywwang@hit.edu.cn (Y.W.)
2 Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, 97187 Luleå, Sweden; weizhuo.lu@ltu.se (W.L.); thomas.olo@ltu.se (T.O.); mats.em@ltu.se (M.E.); jonny.nilimaa@ltu.se (J.N.)
3 Department of Mechanical and Industrial Engineering, Northeastern University, Boston, MA 02115, USA; m.dehghanimommadabadi@northeastern.edu
*Correspondence: kailunfeng@hit.edu.cn

Received: 1 April 2020; Accepted: 28 April 2020; Published: 7 May 2020

Abstract: In many cold regions around the world, such as northern China and the Nordic countries, on-site concrete is often cured in cold weather conditions. To protect the concrete from freezing or excessively long maturation during the hardening process, contractors use curing measures. Different types of curing measures have different effects on construction duration, cost, and greenhouse gas emissions. Thus, to maximize their sustainability and financial benefits, contractors need to select the appropriate curing measures against different weather conditions. However, there is still a lack of efficient decision support tools for selecting the optimal curing measures, considering the temperature conditions and effects on construction performance. Therefore, the aim of this study was to develop a Modeling-Automation-Decision Support (MADS) framework and tool to help contractors select curing measures to optimize performance in terms of duration, cost, and CO2 emissions under prevailing temperatures. The developed framework combines a concrete maturity analysis (CMA) tool, a discrete event simulation (DES), and a decision support module to select the best curing measures. The CMA tool calculates the duration of concrete curing needed to reach the required strength, based on the chosen curing measures and anticipated weather conditions. The DES simulates all construction activities to provide input for the CMA and uses the CMA results to evaluate construction performance. To analyze the effectiveness of the proposed framework, a software prototype was developed and tested on a case study in Sweden. The results show that the developed framework can efficiently propose solutions that significantly reduce curing duration and CO2 emissions.

Keywords: cold climate; discrete event simulation; concrete maturity analysis; curing measures; decision support

1. Introduction

Concrete is heavily used in buildings and infrastructure projects worldwide. According to the World Business Council for Sustainable Development (WBCSD) [1], about 25 billion tons of concrete are produced globally every year. Nearly 1.8 billion tons of ready-mixed concrete are produced and used in China in 2018 [2]. In Nordic countries, including Norway, Finland, Sweden, and Denmark,
the production quantity of ready-mixed concrete was 14.2 million m³ in 2017 [3]. Concrete is used in myriads of construction projects in cold weather conditions, in regions such as the Nordic countries and northern China. In this context, cold weather for concrete is defined as a period of more than three successive days when the average daily air temperature drops below 5 °C (41 °F) and stays below 10 °C (50 °F) for more than one and a half of a 24-h period [4]. Figure 1 shows the average monthly temperatures in some cities where the average temperature is below 5 °C for 3–7 months of the year [5–11].

![Figure 1. Average monthly temperatures of selected cities.](image)

In cold weather, concrete strength develops more slowly, and the curing time needed to reach the required strength is longer than in warmer conditions [12,13]. This negatively affects the removal and reuse of formwork, delays the beginning of subsequent operations, and consequently increases the overall time and cost of projects [14,15]. In Canada, an additional 5%–10% in total construction costs are observed [16]. A case project of dam spillways in USA demonstrated an $750,000 rise in cost that was caused by winter protection measures [17].

To prevent the negative impacts of cold climate on the concrete hardening process, curing measures are taken, including:

1. Thermal curing: The use of heating cables, infrared radiation or hot steam during concrete curing (usually during the first 24 hours after casting concrete) provides a warmer environment for the cast concrete. Thermal curing accelerates concrete hardening but may increase the environmental and economic impacts [18,19].

2. Hot concrete casting (also known as thermal storage curing): This measure increases the temperature of the concrete mix by using warmer water during the concrete mixing process. It requires heating of the mixing water, which increases costs and greenhouse gas (GHG) emissions.

3. Using higher-strength concrete or chemical admixtures: Using higher-strength concrete with more Ordinary Portland Cement (OPC) or chemical admixtures, rather than thermal curing, also accelerates the concrete hardening process [20,21]. However, using more OPC or chemical admixtures than necessary increases the construction cost and GHG emissions [22,23].

4. Coverage and insulation of concrete surfaces: The use of various kinds of coverage and thermal insulation reduces heat losses from hardening concrete. A study of three cases in Stockholm, Malmö, and Umeå has shown that coverage and insulation can be effective when curing at “normal” temperatures (above the “cold” range defined above). However,
at lower temperatures, solely using coverage and insulation without heating can increase project duration [14].

5. Adjustment of project schedule (also called indirect curing measures): This measure involves project managers taking decisions to accelerate or delay construction schedules to avoid or reduce the effects of cold weather. Using indirect curing measures, concrete can be cured in warmer conditions, in which there may be no need for thermal curing or other protective measures. Thus, the additional costs and GHG emissions associated with using curing measures can be saved. However, the delays and acceleration of other activities besides concrete curing can extend project duration or cause additional costs.

Combinations of the measures mentioned above provide varying degrees of protection for the concrete from cold weather during curing. Each of these solutions has different effects on project duration, cost, and GHG emissions. As construction proceeds, weather conditions at the project site will change and a previously selected sustainable curing measure may become unsuitable. Thus, finding appropriate curing measures for every part of the concrete construction process, which starts on different time under different weather conditions, is crucial. In practice, contractors usually decide curing measures according to a rule of thumb, without thoroughly analyzing the combined effects of weather and curing measures on construction performance. Better protection raises costs and GHG emissions, while insufficient protection prolongs project duration. Therefore, there is a clear need to analyze the effects of weather conditions on every concrete curing process and identify the best measures to maximize the sustainability and cost-effectiveness of cast concrete. However, there is still a lack of efficient decision support tools to assist the selection of appropriate curing measures, considering prevailing temperatures and effects on construction performance.

The Maturity Method is a traditional technique for estimating the compressive strength of concrete [24]. Concrete maturity analysis (CMA) tools derived from the Maturity Method, e.g., software such as PPB [25] and Hett [26], have provided ways to capture weather effects on concrete hardening. The Maturity Method can be used to predict concrete’s mechanical properties (i.e., the early and final strength development) by analyzing the combined effects of curing measures and temperature on concrete [23,27,28]. However, knowledge of the effects of curing measures on concrete’s mechanical properties is not enough for contractors to select optimal decisions regarding curing measures. For this, they need to consider the effects of the curing on construction performance parameters (i.e., time, cost, and GHG emissions). For example, two curing measures may have nearly identical effects on concrete’s mechanical properties, but still have very different outcomes on the construction performance [18]. In addition, CMA cannot be directly used to calculate the effects of curing measures on construction performance due to the complex and dynamic interactions between construction activities and weather. The essential input for CMA, weather data, depends on when the curing starts, which is affected by the construction sequences and resource allocations of prerequisite activities. Similarly, the curing of concrete is directly affected by the weather, and its duration affects the following construction activities, which can only start when the concrete has reached a certain strength. Manually analyzing such dynamic and complex interactions is difficult and consumes a lot of time and effort. Hence, CMA must be complemented with an analysis of the effects of possible measures on project performance parameters, such as duration, cost, and GHG emissions, to support the decision of curing measures.

Therefore, the aim of this study was to develop a Modeling-Automation-Decision Support (MADS) framework and tool, combining Maturity Method-based CMA tools and discrete event simulation (DES) to analyze the effects of possible curing measures in cast-in-situ concrete construction projects. The proposed framework provides decision support for contractors to choose curing measures in every weather condition during construction to optimize performance in terms of duration, cost, and CO2 emissions. In this framework, the CMA tools is used to calculate the duration of concrete curing needed to reach the required strength, based on the chosen curing measures and anticipated weather conditions. The DES simulates all construction activities, provides curing start time for the CMA, and uses curing duration calculated by the CMA tool to analyze the effects of curing measures on construction performance parameters. To test the
effectiveness of the developed framework, a prototype combined with several software is developed and applied in a case study of a typical Swedish concrete construction project.

The rest of this paper is structured as follows. Section 2 presents the background of the Maturity Method and DES. The developed framework and prototype software are described in Sections 3 and 4, respectively. The case study used to test their effectiveness is presented in Section 5. Finally, in Section 6, the results are presented and discussed, then conclusions regarding the developed method are provided.

2. Background

2.1. Maturity Method and Concrete Maturity Analysis Tools

Concrete strength development for a specific mix is determined by both time and temperature [29]. In a laboratory environment where the temperature is fully controlled, the strength of concrete can be easily predicted. However, predicting the strength of concrete is more complex in construction practice because the weather conditions, such as the ambient temperature, constantly change during the curing concrete process on construction sites [30]. To address this complexity, the Maturity Method is used for the estimation of concrete strength in actual construction practice [31]. The Maturity Method provides an approach to measuring the time-temperature history and establishes connections between the time-temperature history and the concrete strength [24]. According to the “Standard Practice for Estimating Concrete Strength by the Maturity Method (ASTM C 1074)”, published by the American Society of Testing and Materials (ASTM) [27], the time-temperature history of concrete can be estimated in two ways. The first involves the use of a variable called the maturity index, as shown in Equation (1):

\[ M(t) = \sum (T - T_0) \Delta t \]

where \( M(t) \) (°C-hours) is the maturity index at time \( t \); \( T \) is the average concrete temperature during time interval \( \Delta t \); and \( T_0 \) is the datum temperature (the minimum temperature at which cement can hydrate).

The other method is to evaluate the equivalent age of concrete from the time-temperature history, as shown in Equation (2):

\[ t_e = \sum e^{-Q(1/T - 1/T_0)} \Delta t \]

where \( t_e \) is the equivalent age of concrete at the reference temperature; \( Q \) is a constant specific to the concrete recipe; \( T_0 \) is the reference temperature; and \( T \) is the average temperature during time interval \( \Delta t \).

For each concrete recipe, the relation between strength and time-temperature history should be established in advance as the strength-maturity database. The database is compiled from tests of specimens in laboratory environments and construction sites [27]. The actual time-temperature history of cast-in-situ concrete should then be estimated, considering both the curing measures and weather conditions at the project site. The actual time-temperature history of concrete can then be used together with the established strength-maturity database to predict the strength of concrete.

Many studies have analyzed the effects of curing measures and weather conditions on concrete. For example, Ionov et al. [32] studied the effects of thermal curing and anti-freezing agents on growth of concrete strength. Jung et al. [23] analyzed the effects of heating methods on concrete strength in cold temperatures. Fjellström et al. [28] presented a model to describe the connections between temperature and the strength development of concrete. Based on results from these studies, Maturity Method-based CMA tools have been developed, such as the software PPB [25] and Hett [26]. These tools generate the time-temperature histories after casting concrete and predict the strength development of concrete based on concrete recipes, the geometry of the cast elements, weather conditions, and curing measures.
However, CMA tools have several limitations for helping contractors make decisions regarding curing measures:

1. The CMA tools only provide estimates of concrete’s mechanical properties, which are insufficient for contractors to identify optimal curing measures. Normally, contractors also need information about the effects of curing measures on construction performance parameters, like time, cost, and GHG emissions. A study conducted by Choi et al. [18] found that different types of microwave heating curing can result in very similar concrete strength after 15 days, but nearly 30% variations in curing costs and CO₂ emissions. Therefore, to use CMA tools to support decisions about curing measures, the concrete’s mechanical properties must be linked to construction performance parameters.

2. The dynamic interactions between the constantly changing weather and construction activities strongly affect inputs for the Maturity Method. The major difference between using the Maturity Method in the laboratory and on project sites is that the weather conditions on sites are always changing. Using rough weather estimates, like average monthly temperatures, as CMA inputs leads to inaccurate predictions of concrete strength development. However, more detailed weather data for concrete curing, like hourly temperatures, are affected by the dynamic effects of weather on construction activities. The start time of concrete curing is the finish time of the prerequisite activities. Thus, changes in the parameters of other construction activities, such as the labor, equipment, and time intervals between activities, can affect the curing start time and the weather. The complexity of the analysis increases when effects of curing measures for multiple concrete elements (e.g., for a standard floor) must be considered, as each cast element will affect the start time of all subsequent casting and curing processes. Manual analysis of such dynamic problems requires excessive time and effort not suitable for short-term decision dependent on the latest weather forecasts. Thus, an automatic method to analyze the dynamic interactive effects of construction and weather variables is needed for the application of CMA in construction practice.

2.2. Discrete Event Simulation

Building construction is often a complex process in which the construction activities have complex interactions with each other [33]. Discrete event simulation (DES) is a computer-based technique used to analyze systems by simulating changes in their status resulting from events that occur at particular time instant [34]. In a DES model for a construction system, the triggering event is usually the completion of a construction activity. At that time instant, the status for the construction system, such as construction duration and resource consumption, are changed. The DES has been widely implemented in the construction industry and construction-related studies [35]. For example, Zhang and Li [36] used DES and heuristic algorithm-based optimization to analyze and minimize construction duration, considering interactions between construction activities under resource constraints. Similarly, Feng et al. [37] presented an approach combining DES and a particle swarm optimization algorithm to optimize the performance of construction projects in terms of environmental factors, cost, and time. More generally, the implementations of DES in construction-related studies have shown that it is an effective tool for capturing the complex interactions between construction activities in the systems [38].

In addition, DES can also be used to analyze problems with dynamic conditions, like weather conditions [39], and flexible input parameters, like construction resource plans [36]. For example, Li et al. [40] used an integrated DES and genetic algorithm (GA) optimization approach to analyze the CO₂ emissions of a project under dynamic weather conditions and different labor allocation plans. Shahin et al. [39] proposes a framework to consider the impact of dynamic weather conditions on construction in DES. Larsson and Rudberg [41] analyzed the difference of construction performance between considering or not considering the weather impact at the project site using DES.
Therefore, DES has the ability to compensate for the weakness that CMA tools have in analyzing dynamic interactions between weather and construction activities and calculating the effects of weather and curing measures on construction performance parameters. In the meantime, DES requires CMA-based estimates of the time needed for concrete to reach the strength required to simulate the construction processes more accurately. Originally, DES itself has no function for estimating concrete strength and predicting how long can the cast concrete reach required strength and the follow-up works start. In previous studies, the concrete curing time was often considered as a constant, like 24 hours in Turner and Collins [42]. Thus, the combination of DES and CMA tools provides a possible approach for extending the application of DES in construction planning and the analysis of the concrete curing process.

3. Method

The Modeling-Automation-Decision Support tool developed to help contractors identify optimal curing measures for prevailing weather conditions is shown in Figure 2. It incorporated procedures for combining DES and CMA to analyze the effects of curing measures on construction performance under changeable weather conditions and has three modules. The first module simulated the concrete curing activities and other construction activities. The second module automatically exchanged information between construction simulations, a weather database, concrete maturity database, and an environmental impact database. It also calculated construction performance in terms of predicted duration, costs, and emissions if considered curing measures were applied. The third was a decision support module to compare the curing measures based on their effects on the considered construction performance parameters. The modeling and automation modules calculated the curing duration, cost, and GHG emissions associated with all the alternative curing measures introduced to the MADS tool. The decision support module then compared the curing measures based on the calculated construction performance and output the optimal curing measures for the contractors. The method was designed for short-term decisions, like selecting curing measures for a standard floor, since sufficiently accurate weather forecasts can only be acquired close to the start date.

![Schematic diagram of the MADS framework.](image)

3.1. Module 1: Modeling Construction Activities

The simulation model was based on a generalized simulation model called the CARS proposed by Fischer et al. [43]. The CARS included the project information required to describe the
interactions between activities and simulate construction activity. In CARS, C represented the building components under construction; A was the construction activities for the components; R was the resource required by the construction activities, e.g., labor or equipment; and S denoted the sequencing constraints linking construction activities. The related project information for the simulation, including the sequences and logic connections between construction activities, resource allocation, productivity of resource, and quantity of work in each construction activity, were collected from the contractors’ construction planning documents.

3.2. Module 2: Automatic Information Exchange and Calculation

The automation module was used for automatic calculation of performance parameters. This module exchanged relevant data among the simulation model (Module 1), the CMA tools, the weather database, and the environmental impact database. First, Module 1 calculated the curing start time. Module 2 then automatically paused Module 1 and used the curing start time from the simulation to extract a weather forecast from the weather database. Next, the extracted weather information was input into the CMA to predict the maturity of the concrete elements. The curing time needed to reach the required strength of concrete was then extracted and input into the Module 1. After receiving the feedback, the simulation continued from where it was paused. The above processes were repeated until the simulation finished, with all curing activities being simulated. After that, the effects of all considered curing measures on three project performance parameters (duration, cost, and CO₂ emissions) were then evaluated. To remove the impact of project quantities on the results, CO₂ emissions and costs in the results were divided by the area of a standard floor, and the reference unit was 1 m². The calculation of duration, cost, and CO₂ emissions are presented below.

1. Duration of construction activities

Construction activities in the simulation model were divided into concrete curing activities and other construction activities. The duration of each concrete curing activity was calculated by CMA. The duration of other construction activities depended on the allocation of construction resources, productivity of the resources, and quantity of work associated with each specific construction activity, as summarized by Equation (3):

\[ Time = \frac{Q}{P \times R} \]  

(3)

where \( Time \) denotes the duration of the construction activity; \( Q \) means the quantity of work that should be finished in the activity; \( R \) refers to resources allocated for this activity, e.g., workforce or equipment; and \( P \) is the productivity of the allocated resources.

Construction activities were linked through construction sequences. Sometimes, some construction activities happen at the same time. Thus, the total construction duration was not a simple sum of duration of all activities, but the sum of duration of activities on the critical path. A critical path refers to the sequence of construction activities which add up to the longest overall duration. To analyze the effect of curing measures on construction duration, the duration of all curing activities on the critical path was added up. Simulation can automatically identify the curing activities on the critical path and calculate the total duration of curing activities.

2. Curing cost

Curing cost was the additional cost caused by the application of curing measures. It included the costs of external heating \( (C_{\text{Heating}}) \), mixing concrete \( (C_{\text{Mixing}}) \), using coverage and insulation \( (C_{\text{Coverage&Insulation}}) \), and changing concrete type \( (C_{\text{ChangingConcrete}}) \), as shown in Equation (4):

\[ Cost = C_{\text{Heating}} + C_{\text{Mixing}} + C_{\text{Coverage&Insulation}} + C_{\text{ChangingConcrete}} \]  

(4)
The cost of external heating refers to the operational and rental or purchase costs of heaters, like heating fans or heating cables. The cost of mixing concrete refers to the fees for heating water used to mix concrete. The cost of using coverage and insulation refers to the extra cost arising from using coverage on slabs and adding insulation on formwork. The cost of changing concrete type refers to the additional cost of using higher-grade concrete, which equals the difference between the costs of the actually used concrete and the designed concrete.

3. CO₂ emissions caused by curing

CO₂ emissions calculated in this method refer to the increase in CO₂ equivalents caused by using curing measures, including external heating (CO₂-eqHeating), hot concrete casting (CO₂-eqMixing), and changing concrete type (CO₂-eqChangingConcrete), as shown in Equation (5). Since the coverage and insulation can be used many times during construction, the CO₂ equivalents, due to use of coverage and insulation materials, were very small and neglected here. CO₂ emissions were calculated by the automation module, which connected simulations with an environmental impact database. The environmental impact data can be found in the environmental product declaration (EPD) or previous studies.

For external heating and hot concrete casting, the analyzed system boundary was limited to construction. The CO₂ emissions caused by these two measures were calculated by the energy consumption multiplied by the global warming potential (GWP) factors for the consumed energy, as shown in Equation (6). The system boundary for changing concrete was from cradle to preproduction, including the exploitation and transportation of raw materials. Different grades of concrete have little impact on the production, concrete transportation, and casting activities. Thus, the difference in CO₂ emissions caused by using higher-grade concrete in manufacturing, transporting and casting concrete was neglected. The CO₂ emissions of changing concrete type were calculated based on the GWP factors from cradle to preproduction multiplied by the quantity of concrete, as shown in Equation (10):

\[
\text{CO}_2\text{-eq} = \text{CO}_2\text{-eqHeating} + \text{CO}_2\text{-eqMixing} + \text{CO}_2\text{-eqChangingConcrete}
\]  

(5)

where CO₂-eqHeating means the CO₂ emissions caused by the consumption of energy, usually electricity or diesel, by heaters during heating concrete; and CO₂-eqMixing refers to the CO₂ emissions associated with the energy consumed by heating the concrete during mixing. Both CO₂-eqHeating and CO₂-eqMixing can be calculated according to Equation (6):

\[
\text{CO}_2\text{-eqHeating or CO}_2\text{-eqMixing} = \sum \text{GWP}_{Energy} \times \text{Energy}
\]

(6)

where Energy is the energy consumed due to the use of external heating or hot concrete measures, and energy consumed by heating is calculated through energy consumption of heaters per unit time multiplied by curing time; and GWP_{Energy} denotes the global warming potential factor of the energy used.

According to Zhu [44], the mixing temperature of concrete (the temperature of concrete leaving the mixer) can be calculated using Equation (7):

\[
T_0 = \frac{(c_s + c_n q_s)W_s T_s + (c_g + c_n q_g)W_g T_g + c_r W_r T_r + c_w (W_w - q_s W_s - q_g W_g)T_w}{c_s W_s + c_g W_g + c_r W_r + c_w W_w}
\]

(7)

where \(T_0\) is the mixing temperature of concrete; \(c_s, c_g, c_r, c_w\) are the specific heat capacities of fine aggregates, coarse aggregates, cement, and water, respectively; \(q_s\) and \(q_g\) are the water contents (%) of fine and coarse aggregates, respectively; \(W_s, W_g, W_r, W_w\) are the weights of fine aggregates, coarse aggregates, cement and water per m³ of concrete, respectively; and \(T_s, T_g, T_r, T_w\) are the temperatures of fine aggregates, coarse aggregates, cement, and water before mixing, respectively.
A common hot concrete casting method uses warmer water than normal during concrete mixing. To estimate the required increase in water temperature, Equation (7) can be modified, as shown in Equation (8):

\[
T_w = \frac{T_0 (c_w W_w + c_g W_g + c_c W_c) - (c_w + c_g q_g) W_c T_c - (c_g + c_q q_g) W_g T_g - c_w T_c}{c_w (W_w - q_g W_g - q_g W_g)}
\]

(8)

Hence, the energy consumed by heating the water used in concrete mixing can be calculated as Equation 9:

\[
CO_{2-equMixing} = GWPEnergy c_w (T_w - T_0) W_w
\]

(9)

where \(T_0\) is the temperature of water before heating.

According to Zhu [44], the parameters for calculating the temperature of the mixing concrete parts are:

\[c_w = c_g = c_c = 0.837 \text{ kJ/(kg} °\text{C}), c_w = 4.19 \text{ kJ/(kg} °\text{C}).\]

\(CO_{2-equChangingConcrete}\) is the difference in CO\(_2\) emissions caused by changing the concrete type from the basic designed concrete to higher-grade concrete, as shown in Equation (10):

\[
CO_{2-equChangingConcrete} = GWPUseConcrete QUseConcrete - GWPCvisedConcrete QDesignedConcrete
\]

(10)

where \(QUseConcrete\) refers to the quantities of materials in the changed concrete (fine or coarse aggregates, cement, and admixtures); \(GWPUseConcrete\) refers to the GWP factors from cradle to preproduction of the changed concrete; \(QDesignedConcrete\) refers to the quantities of materials in the original designed concrete; and \(GWPCvisedConcrete\) refers to the GWP factors from cradle to preproduction of the original designed concrete.

The values of the three parameters (cost, duration, and emissions) estimated from the above equations reflected the direct effects of curing measures on construction performance. Curing measures also have some indirect effects. For example, the CO\(_2\) emissions caused by lights at the project site are affected by the construction duration and increase when curing time is prolonged. Prolonged curing duration can also cause delays in finishing construction activities, leading to penalty fees and extra costs. These indirect effects are significantly influenced by factors other than curing measures, and, thus, they were not considered in this study.

3.3. Module 3: Decision Support for Curing Measures

After modeling the construction and automation of information exchange, the effects of the considered curing measures on construction objectives were calculated. Information regarding the contractors’ preferences on the construction performance parameters (for example, equal weighting for the construction duration, cost, and GHG emissions) from Module 1 and 2 entered the decision support module. Based on contractors’ preferences, the decision support module then proposed the best combinations of considered curing measures for the specified conditions. Contractors also usually have specific requirements for some objectives, for example, constraints for the construction duration. The selected best curing measures should also meet those requirements.
4. Prototype

Based on the proposed framework, a prototype was built to assess the method’s effectiveness. In this prototype, SIMIO (a DES platform) was used for modeling the construction activities. The automation module integrated several programs. The MySQL database engine was used to store the weather data during the whole construction period and exchange data between programs. MATLAB scripts were used as interfaces between programs to execute program calling and data exchange. Hett (version 2.5 is used) developed by [26] served as the CMA tool that calculated the development of concrete strength over time. The decision support module was built in MATLAB, which received the calculated construction performance parameters and compared the curing measures. The interactions between different parts of the prototype are illustrated in Figure 3.

![Figure 3](image-url)  
**Figure 3.** Schematic diagram of the workflow of the developed SIMIO–Hett prototype.

The functions of the programs used in the prototype are described below.

1. SIMIO

The DES model was designed to analyze interactions of construction activities and calculate effects of curing measures on construction performance. In SIMIO, construction activities are represented by the *Servers*, and the *Paths* connect *Servers* according to the construction sequences (Equations 3–10) are provided through *Processes* in SIMIO. *Processes* are linked to the *Paths* and *Servers* in order to calculate the construction performance based on the allocation of resources, productivity and quantities of work stored in SIMIO. To connect SIMIO and MATLAB, a special user defined *Process* called CallMATLAB is used. Details of CallMATLAB’s development are described by Dehghanimohammadabadi et al. [45] and Dehghanimohammadabadi and Keyser [46]. CallMATLAB can run a MATLAB script during simulation runs, and the simulation pauses until the MATLAB script is finished. To exchange data between SIMIO and other programs, *Process DBwrite* and *DBread* were used. When a simulation was finished, the results were transferred back into MATLAB.
2. MySQL database

The MySQL database in the prototype had two purposes: to store hourly weather data for the whole construction period, and to store the processing data exchanged between SIMIO and MATLAB during simulation runs. The processing data included curing start time, concrete recipes, curing measures, and formwork removal time. SIMIO can write and read data to/from the MySQL database. Open Database Connectivity (ODBC) provides the connection between MySQL and MATLAB.

3. Concrete maturity analysis tool (Hett)

The CMA tool used in the prototype was Hett. The input parameters, including the concrete geometries and recipes, curing measures, and weather data, were defined in a text-based input file of Hett. Hett reads the input file, calculates the strength of concrete at specified time intervals after casting, and writes the results into a text-based output file.

4. MATLAB

MATLAB is used as an interface that executes programs and exchanges data between SIMIO and Hett. When SIMIO triggers CallMATLAB Process, a MATLAB script is run. The script reads data from the MySQL database and writes the data into the input file of the CMA tool, Hett. MATLAB then executes Hett and reads results from the output file concerning concrete strength development over time after casting. The time when concrete reaches the required strength is defined as the curing finish time and will be transferred to SIMIO. MATLAB was also used for the decision support module in the prototype after calculating the effects of all the considered curing measures. A MATLAB-based guided user interface (GUI) was developed (as shown in Figure 4) to allow users to input details of curing measures (e.g., the temperature of hot concrete or the heating effect of heating cables). Weather conditions can also be defined through the interface. After all input variables were defined, the GUI transferred the data into the prototype and executed the simulation. The results of the simulation are shown in the bottom left part of the GUI.

![Figure 4. Guide user interface of the prototype.](image-url)
5. Case Study

5.1. Case Background

To demonstrate the DES-CMA method’s effectiveness, this section presents an application of the developed prototype to a case project, in which a seven-story building was constructed using cast-in-situ concrete in Nordmaling, northern Sweden. The case building went through cold weather for several months during construction. The quantity of work, productivity, consequences, resource allocation, curing measures, cost, and electricity consumption of the construction activities came from construction documents and interviews with site managers.

The construction sequence of a standard floor in the building structure is shown in Figure 5. The walls in a standard floor were casted in five cycles. Each wall cycle repeated the same construction activities. The construction of the slab only starts when all five wall cycles have been finished. The slab in each standard floor was casted as whole. Thus, the concrete structures in a standard floor were casted six times: five for walls, and one for the slab. The calculation of duration considers the working schedule: casting and curing concrete can be conducted any time of the day, while other construction activities are only conducted from 9:00 a.m. to 5:00 p.m. In a standard floor, the quantities of concrete used in walls and the slabs were 52.425 and 64.148 m³, respectively. The size of slabs in a standard floor were 312.918 m² with thickness of 205 mm. The size of walls in a standard floor were 238.295 m² with thickness of 220 mm. The GWP factors (for 100 years lifetime) of materials and energy consumption used in the case are shown in Table 1.

According to the construction documents, the wall formwork could be removed when the strength of the hardening concrete reached 5 MPa. Removal of the supporting formwork from slabs and the following construction activities cannot start until the hardening concrete reached 70% of the designed strength, which is 70% × 30 = 21 MPa.

Table 1. Global Warming Potential (GWP) factors.

<table>
<thead>
<tr>
<th>GWP</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>0.668 kg CO₂-eq/kg [47]</td>
</tr>
<tr>
<td>Water</td>
<td>0.000321 kg CO₂-eq/kg [48]</td>
</tr>
<tr>
<td>Fine aggregates</td>
<td>0.0139 kg CO₂-eq/kg [49]</td>
</tr>
<tr>
<td>Coarse aggregates</td>
<td>0.0459 kg CO₂-eq/kg [49]</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.056 kg CO₂-eq/kWh [50]</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.080 kg CO₂-eq/MJ [51]</td>
</tr>
<tr>
<td>Plasticizers</td>
<td>0.2295 kg CO₂-eq/kg [52]</td>
</tr>
</tbody>
</table>

![Figure 5. Sequences of construction activities.](image-url)
5.2. Weather Conditions During Construction

The case project started on November 20, 2017 and finished on June 30, 2018. Data on the weather conditions at the project site during the entire construction period (illustrated in Figure 6) were collected from a local weather station. The on-site temperature varied significantly during construction, from −22.2 °C to 26.6 °C. The estimated wind at the case project location was mild (<2 m/s) during the construction period. To test the effects of different weather conditions on optimal curing measures, three typical types of weather during the construction were chosen as weather inputs for the developed prototype. The three weather conditions were recorded from November 20 to December 20, 2017 (temperature around 0 °C); from May 20 to June 20, 2018 (warm weather); and from February 20 to March 20, 2018 (cold weather). Historical weather conditions were used in this case study because it was conducted after construction was finished. To apply the developed prototype software in a project under construction, predicted weather conditions can be used.

![Temperature graph](image)

**Figure 6.** Hourly temperatures during the construction of the case building structure.

5.3. Curing Measures

The curing measures and parameters gathered from construction documents and interviews with the contractors and entered into the prototype in the case are shown in Tables 2, 3, and 4. These curing measures can be applied independently, and contractors will normally use a combination of them. The rental cost of heaters is calculated according to construction days. For using hot concrete, the temperature of tap water at project site is assumed to be 20 °C. If the temperature of water used for mixing concrete calculated by Equation (8) is lower than 20 °C, then the water does not need to be heated so heating water causes no CO₂ emissions. In this case, changing number of the workers from 10 to 15 is assumed to cause no changes in working efficiency or unit salary per worker.

<table>
<thead>
<tr>
<th>Curing Measure</th>
<th>Details</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot concrete</td>
<td>Concrete temperature when curing starts: 5°C</td>
<td>WA1</td>
</tr>
<tr>
<td></td>
<td>Concrete temperature when curing starts: 25°C</td>
<td>WA2</td>
</tr>
<tr>
<td>Heating</td>
<td>Heating cables, heating effect: 12 kW</td>
<td>WB1</td>
</tr>
<tr>
<td></td>
<td>Heating cables, heating effect: 6 kW</td>
<td>WB2</td>
</tr>
<tr>
<td>Coverage and insulation</td>
<td>12 mm plywood formwork with insulation, heat transfer coefficient: 1.8 W/(m² K) (when wind speed is lower than 2 m/s)</td>
<td>WC1</td>
</tr>
<tr>
<td></td>
<td>12 mm plywood formwork without insulation, heat transfer coefficient: 5.4 W/(m² K) (when wind speed is lower than 2 m/s)</td>
<td>WC2</td>
</tr>
<tr>
<td>Higher-grade concrete</td>
<td>C25/30, standard Portland cement</td>
<td>WD1</td>
</tr>
<tr>
<td></td>
<td>C28/35, standard Portland cement</td>
<td>WD2</td>
</tr>
</tbody>
</table>
Table 3. Alternative direct curing measures for slabs.

<table>
<thead>
<tr>
<th>Curing Measure</th>
<th>Details</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot concrete</td>
<td>Concrete temperature when curing starts: 5°C</td>
<td>SA1</td>
</tr>
<tr>
<td></td>
<td>Concrete temperature when curing starts: 25°C</td>
<td>SA2</td>
</tr>
<tr>
<td>Heating</td>
<td>Steam heating, heat effect 48 kW; diesel consumption 4.4 kg/h</td>
<td>SB1</td>
</tr>
<tr>
<td></td>
<td>Steam heating, heat effect 66 kW; diesel consumption 6.07 kg/h</td>
<td>SB2</td>
</tr>
<tr>
<td>Coverage and insulation</td>
<td>Slab coverage, normal tarps, heat transfer coefficient: 8.3 W/(m² K)</td>
<td>SC1</td>
</tr>
<tr>
<td></td>
<td>(when wind speed is lower than 2 m/s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slab coverage, insulated tarps, heat transfer coefficient: 2.7 W/(m² K)</td>
<td>SC2</td>
</tr>
<tr>
<td></td>
<td>(when wind speed is lower than 2 m/s)</td>
<td></td>
</tr>
<tr>
<td>Higher-grade concrete</td>
<td>C25/30, standard Portland cement</td>
<td>SD1</td>
</tr>
<tr>
<td></td>
<td>C28/35, standard Portland cement</td>
<td>SD2</td>
</tr>
</tbody>
</table>

Table 4. Alternative indirect curing measures.

<table>
<thead>
<tr>
<th>Curing Measure</th>
<th>Details</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changing number of</td>
<td>Carpenters, 10; concrete workers, 10; installation workers, 10.</td>
<td>IA1</td>
</tr>
<tr>
<td>workers</td>
<td>Carpenters, 15; concrete workers, 15; installation workers, 15.</td>
<td>IA2</td>
</tr>
<tr>
<td>Changing wall casting</td>
<td>No delay</td>
<td>IB1</td>
</tr>
<tr>
<td>delay</td>
<td>Delay of 15 hours for each wall casting</td>
<td>IB2</td>
</tr>
<tr>
<td>Changing slab casting</td>
<td>No delay</td>
<td>IC1</td>
</tr>
<tr>
<td>delay</td>
<td>Delay of 15 hours</td>
<td>IC2</td>
</tr>
</tbody>
</table>

According to SS-EN 13670:2009 Execution of Concrete structure [53], concrete should not be allowed to freeze until the strength of the hardening concrete reaches 5 MPa. Thus, the concrete heating lasted until the hardening concrete reaches 5 MPa in this case. According to interviews with the contractors, the heating efficiencies of heating cables in walls and steam heating for slabs were 0.9 and 0.5, respectively.

Two optional types of concrete were considered: C25/30 and C28/35. The concrete recipes are shown in Table 5, which also presents the CO₂ emissions of concrete calculated from the relevant quantities of materials multiplied by GWP factors from cradle to preproduction listed in Table 1. As for the heating and hot concrete mixing, the CO₂ emissions are calculated based on the simulated curing duration of each curing activity multiplied by the energy consumption of the used heaters per unit time multiplied by GWP factors for the consumed energy.

Table 5. Concrete recipes and CO₂ emissions.

<table>
<thead>
<tr>
<th>Materials</th>
<th>GWP Factors (kg CO₂-eq/kg)</th>
<th>Concrete Recipes (kg/m³)</th>
<th>CO₂ Emissions (kg CO₂-eq/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>0.668</td>
<td>350</td>
<td>370</td>
</tr>
<tr>
<td>Water</td>
<td>0.0000321</td>
<td>231</td>
<td>196</td>
</tr>
<tr>
<td>Fine aggregates</td>
<td>0.0139</td>
<td>695</td>
<td>701</td>
</tr>
<tr>
<td>Coarse aggregates</td>
<td>0.0459</td>
<td>1106</td>
<td>1096</td>
</tr>
<tr>
<td>Plasticizers</td>
<td>0.2295</td>
<td>1.35</td>
<td>1.60</td>
</tr>
</tbody>
</table>

5.4. Scenarios

Based on the alternatives listed in Tables 2, 3, and 4, 76 combinations of measures were used to test the effects of different curing measures on construction performance, as shown in Table 6. The combinations were categorized into three groups. The combinations A1–A64, B1–B4, and C1–C8 were designed to test the effect of thermal protection, using concrete with different strengths, and
the indirect curing measures on construction performance, respectively. The combinations A1, B1, C1 were used as reference combinations and included the same curing measures. All the combinations were analyzed under the three types of weather conditions to illustrate the effects of weather conditions on curing measure decisions.

Table 6. Tested combinations of curing measures.

<table>
<thead>
<tr>
<th>No.</th>
<th>Curing Measures</th>
<th>No.</th>
<th>Curing Measures</th>
<th>No.</th>
<th>Curing Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>WA1, WB1, WC1, SA1, SB1, SC1;</td>
<td>A27</td>
<td>WA1, WB2, WC2, SA1, SB2, SC1;</td>
<td>A52</td>
<td>WA2, WB2, WC1, SA1, SB2, SC2;</td>
</tr>
<tr>
<td>A2</td>
<td>WA1, WB1, WC1, SA1, SB2, SC2;</td>
<td>A28</td>
<td>WA1, WB2, WC2, SA1, SB2, SC2;</td>
<td>A53</td>
<td>WA2, WB2, WC1, SA2, SB1, SC1;</td>
</tr>
<tr>
<td>A3</td>
<td>WA1, WB1, WC1, SA1, SB2, SC1;</td>
<td>A29</td>
<td>WA1, WB2, WC2, SA2, SB1, SC1;</td>
<td>A54</td>
<td>WA2, WB2, WC1, SA2, SB1, SC2;</td>
</tr>
<tr>
<td>A4</td>
<td>WA1, WB1, WC1, SA1, SB2, SC2;</td>
<td>A30</td>
<td>WA1, WB2, WC2, SA2, SB1, SC2;</td>
<td>A55</td>
<td>WA2, WB2, WC1, SA2, SB2, SC1;</td>
</tr>
<tr>
<td>A5</td>
<td>WA1, WB1, WC1, SA2, SB1, SC1;</td>
<td>A31</td>
<td>WA1, WB2, WC2, SA2, SB2, SC1;</td>
<td>A56</td>
<td>WA2, WB2, WC1, SA2, SB2, SC2;</td>
</tr>
<tr>
<td>A6</td>
<td>WA1, WB1, WC1, SA2, SB2, SC1;</td>
<td>A32</td>
<td>WA1, WB2, WC2, SA2, SB2, SC2;</td>
<td>A57</td>
<td>WA2, WB2, WC2, SA1, SB1, SC1;</td>
</tr>
<tr>
<td>A7</td>
<td>WA1, WB1, WC1, SA2, SB1, SC1;</td>
<td>A33</td>
<td>WA1, WB1, WC1, SA1, SB1, SC1;</td>
<td>A58</td>
<td>WA2, WB2, WC2, SA1, SB1, SC2;</td>
</tr>
<tr>
<td>A8</td>
<td>WA1, WB1, WC1, SA2, SB1, SC2;</td>
<td>A34</td>
<td>WA2, WB1, WC1, SA1, SB1, SC2;</td>
<td>A59</td>
<td>WA2, WB2, WC2, SA1, SB2, SC1;</td>
</tr>
<tr>
<td>A9</td>
<td>WA1, WB1, WC2, SA1, SB1, SC1;</td>
<td>A35</td>
<td>WA2, WB1, WC1, SA1, SB2, SC1;</td>
<td>A60</td>
<td>WA2, WB2, WC1, SA1, SB2, SC2;</td>
</tr>
<tr>
<td>A10</td>
<td>WA1, WB1, WC2, SA2, SB1, SC1;</td>
<td>A36</td>
<td>WA2, WB1, WC1, SA2, SB2, SC1;</td>
<td>A61</td>
<td>WA2, WB2, WC2, SA2, SB1, SC1;</td>
</tr>
<tr>
<td>A11</td>
<td>WA1, WB1, WC2, SA1, SB2, SC1;</td>
<td>A37</td>
<td>WA2, WB1, WC1, SA2, SB1, SC1;</td>
<td>A62</td>
<td>WA2, WB2, WC2, SA2, SB1, SC2;</td>
</tr>
<tr>
<td>A12</td>
<td>WA1, WB1, WC1, SA2, SB2, SC1;</td>
<td>A38</td>
<td>WA2, WB1, WC1, SA2, SB2, SC2;</td>
<td>A63</td>
<td>WA2, WB2, WC2, SA2, SB2, SC1;</td>
</tr>
<tr>
<td>A13</td>
<td>WA1, WB1, WC2, SA2, SB1, SC1;</td>
<td>A39</td>
<td>WA2, WB1, WC1, SA2, SB2, SC1;</td>
<td>A64</td>
<td>WA2, WB2, WC2, SA2, SB2, SC2;</td>
</tr>
<tr>
<td>A14</td>
<td>WA1, WB1, WC2, SA2, SB2, SC1;</td>
<td>A40</td>
<td>WA2, WB1, WC1, SA2, SB2, SC2;</td>
<td>B1</td>
<td>WD1, SD1</td>
</tr>
<tr>
<td>A15</td>
<td>WA1, WB1, WC2, SA2, SB2, SC1;</td>
<td>A41</td>
<td>WA2, WB1, WC2, SA1, SB1, SC1;</td>
<td>B2</td>
<td>WD1, SD2</td>
</tr>
<tr>
<td>A16</td>
<td>WA1, WB1, WC2, SA2, SB2, SC2;</td>
<td>A42</td>
<td>WA2, WB1, WC2, SA1, SB2, SC2;</td>
<td>B3</td>
<td>WD2, SD1</td>
</tr>
<tr>
<td>A17</td>
<td>WA1, WB2, WC1, SA1, SB1, SC1;</td>
<td>A43</td>
<td>WA2, WB1, WC2, SA1, SB2, SC1;</td>
<td>B4</td>
<td>WD2, SD2</td>
</tr>
<tr>
<td>A18</td>
<td>WA1, WB2, WC1, SA2, SB1, SC2;</td>
<td>A44</td>
<td>WA2, WB1, WC2, SA1, SB2, SC2;</td>
<td>C1</td>
<td>IA1, IB1, IC1</td>
</tr>
<tr>
<td>A19</td>
<td>WA1, WB2, WC1, SA2, SB2, SC1;</td>
<td>A45</td>
<td>WA2, WB1, WC2, SA2, SB1, SC1;</td>
<td>C2</td>
<td>IA1, IB1, IC2</td>
</tr>
<tr>
<td>A20</td>
<td>WA1, WB2, WC2, SA1, SB1, SC2;</td>
<td>A46</td>
<td>WA2, WB1, WC2, SA2, SB1, SC2;</td>
<td>C3</td>
<td>IA1, IB2, IC1</td>
</tr>
<tr>
<td>A21</td>
<td>WA1, WB2, WC2, SA2, SB1, SC1;</td>
<td>A47</td>
<td>WA2, WB1, WC2, SA2, SB2, SC1;</td>
<td>C4</td>
<td>IA1, IB2, IC2</td>
</tr>
<tr>
<td>A22</td>
<td>WA1, WB2, WC2, SA2, SB2, SC1;</td>
<td>A48</td>
<td>WA2, WB1, WC2, SA2, SB2, SC2;</td>
<td>C5</td>
<td>IA2, IB1, IC1</td>
</tr>
<tr>
<td>A23</td>
<td>WA1, WB2, WC1, SA2, SB1, SC1;</td>
<td>A49</td>
<td>WA2, WB2, WC1, SA1, SB1, SC1;</td>
<td>C6</td>
<td>IA2, IB1, IC2</td>
</tr>
<tr>
<td>A24</td>
<td>WA1, WB2, WC1, SA2, SB2, SC1;</td>
<td>A50</td>
<td>WA2, WB2, WC1, SA1, SB2, SC1;</td>
<td>C7</td>
<td>IA2, IB2, IC1</td>
</tr>
<tr>
<td>A25</td>
<td>WA1, WB2, WC2, SA1, SB1, SC1;</td>
<td>A51</td>
<td>WA2, WB2, WC1, SA1, SB2, SC1;</td>
<td>C8</td>
<td>IA2, IB2, IC2</td>
</tr>
<tr>
<td>A26</td>
<td>WA1, WB2, WC2, SA1, SB1, SC2;</td>
<td>A52</td>
<td>WA2, WB2, WC2, SA2, SB1, SC1;</td>
<td>C9</td>
<td>IA2, IB2, IC2</td>
</tr>
</tbody>
</table>

Note: For A1–A64, IA1, IB1, and IC1 are used. For B1–B4, WA1, WB1, WC1, SA1, SB1, and SC1 are used. For C1–C3, WA1, WB1, WC1, WD1, SA1, SB1, SC1, and SD1 are used.

6. Results and Discussion

6.1. Performance of Curing Measures

The results obtained using the MADS prototype are summarized in the following sections.

1. Hot concrete, thermal curing and insulation (combinations A1–A64)

The results of combinations A1–A64 are shown in Figure 7; Figure 8. In total, 192 scenarios were analyzed (64 combinations of curing measures, each with three weather conditions). The construction performance resulting from a given combination with different weather conditions are linked by lines.

As shown in Figure 7 and 8, curing measures and weather conditions both significantly affected construction performance in terms of time, CO2 emissions, and cost. Generally, using the same curing measures, colder temperatures increased curing time, costs, and CO2 emissions. As the weather gets colder, some curing measures that can provide acceptable construction performance in warmer weather may result in bad performance. For example, combinations A26 and A28 reached short curing duration and low CO2 emissions with reasonably low costs when the temperature was around or above 0°C (e.g., on November 20, 2017 or May 20, 2018). However, when the standard floor was constructed in a colder weather (e.g., on February 20, 2018), the curing duration by using A26 and A28 were significantly prolonged. Choosing curing measures that provide good overall
protection for concrete may keep the curing duration short and stable, even in cold weather, but such measures result in high costs and CO₂ emissions. For example, although A40 provided the strongest protection for concrete, for a standard floor starting construction on May 20, 2018, combinations like A36 and A44 could provide similar curing duration with 1 kg CO₂-equiv/m² less emissions than A40. Importantly, when multiple curing activities are simultaneously considered, changes in the duration of any curing process will affect start time of all subsequent activities. Hence the weather may be warmer or colder during the subsequent curing activities, with inevitable effects on construction performance. Thus, to maximize economic and environmental benefits, contractors should not use the same curing measures throughout a whole project but are advised to analyze the weather conditions and choose curing measures accordingly.

As shown in Figure 8, in some situations curing costs do not increase, despite cold weather prolonging the curing duration. The reason is that the prolonged curing duration in such situations occurs outside working hours, between 5:00 p.m. and 8:00 a.m. Thus, the total number of construction days does not increase. In this case, the rental cost of heaters is calculated according to the construction days and thus does not always increase as the curing duration is prolonged.

Figure 7. The effects of curing measure combinations A1–A64 on duration and CO₂ emissions.

Figure 8. The effects of curing measure combinations A1–A64 on duration and cost.

2. Using higher-grade concrete (combinations B1–B4).

The effects of changing the concrete type on construction performance are shown in Figures 9 and 10. To test the effects of using concrete with different strength, parameters of the reference
combination were used for the other curing measures in 12 scenarios (two concrete types for two building components under three different weather conditions).

Using higher-strength concrete directly reduced the curing duration, leading to increased costs and CO$_2$ emissions of materials and decreased costs and CO$_2$ emissions resulting from heating concrete. Sometimes the reductions in cost and CO$_2$ emissions caused by heating exceeded the increases of materials. For example, combination B2 resulted in lower costs than combination B1.

In the studied scenarios, the reduction in curing duration provided by using higher-grade concrete in the walls was limited, leading to higher costs and CO$_2$ emissions, as shown by comparison of results of combinations B1 versus B3 and B2 versus B4. This is because the concrete in walls only needs to be cured to 5 MPa. Concrete in slabs needs to be cured to 70% of designed 28-day strength, so using higher-strength concrete in slabs has more significant effects. For example, combination B2 resulted in shorter curing duration and lower cost than B1. B2 resulted in higher CO$_2$ emissions than B1, but the difference in CO$_2$ emissions between them declined as the weather got colder. Especially for a standard floor starting construction on February 20, 2018, B1 and B2 would have resulted in very similar CO$_2$ emissions. Thus, in the studied case, using higher-strength concrete in slabs was an appropriate choice for the contractor, especially in cold weather.

3. Indirect curing measures (combinations C1–C8).

Twenty-four scenarios (with eight combinations of curing measures under three weather conditions) indicated the results of indirect curing measures on CO$_2$ emissions, costs, and curing
duration. Indirect curing measures directly change duration of other construction activities, and thus affect the starting time of all subsequent concrete curing processes and the weather conditions. In this case, CO2 emissions were only affected by the curing duration, as shown in Figure 11. Hence, the delay or acceleration of the construction progress and thereby changed weather conditions will affect CO2 emissions. However, the total rental cost of heaters calculated by the total number of construction days will be directly affected if the indirect curing measures prolonged or shortened the construction days, as shown in Figure 12. For example, combination C5 shortened the duration of other construction activities through using more workers, which had limited influence on curing duration and CO2 emissions, but significantly reduced the curing cost.

Appropriate delay/acceleration of the construction progress of other construction activities can result in shorter duration, less costs, and less CO2 emissions. This impact of indirect curing measures is strongly connected to the weather conditions. For example, combinations C3 and C4 delayed the wall casting and resulted in warmer weather for curing concrete walls. The curing duration and CO2 emissions of C3 and C4 were reduced if the construction of the standard floor started on November 20, 2017 or February 20, 2018. However, if the concrete was cast on May 20, 2018, combination C3 or C4 increased the curing duration, cost and CO2 emissions.

![Figure 11](image1.png)  
**Figure 11.** The effects of indirect curing measures on duration and CO2 emissions.

![Figure 12](image2.png)  
**Figure 12.** The effects of indirect curing measures on duration and cost.

6.2. Decision Support for Contractors

The developed prototype can also provide decision support for contractors based on the effects on performance result from the evaluated combinations of curing measures. The selection of optimal measures will depend on the contractor’s preferences on the three construction performance
parameters: duration, cost, and CO₂ emissions. If the contractors consider them equally important, optimal combinations of curing measures can be selected by finding Pareto solutions. The Pareto solutions are often used in problems with multiple objectives and refer to some solutions that are not worse than any other solution in terms of all objectives (here, the minimization of project duration, costs, and CO₂ emissions) simultaneously [54]. Contractors normally have some constraints related to project objectives, and one in the studied case project was that the structures of a standard floor had to be constructed within 12 days. Thus, combinations of curing measures leading to construction duration exceeding 288 hours were excluded. The optimal combinations of curing measures considering different preferences and time restriction are shown in Table 7. The contractors can now select specific optimal combinations of curing measures for the evaluated weather conditions based on their preferences for different construction performance parameters.

Table 7. Optimal curing measures according to different preferences and time constraints.

<table>
<thead>
<tr>
<th>Construction Start Time</th>
<th>Shortest Curing Duration</th>
<th>Lowest Curing-Caused CO₂ Emissions</th>
<th>Least Curing Cost</th>
<th>Pareto Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 20 2018</td>
<td>A40</td>
<td>A18</td>
<td>A58</td>
<td>A2, A4, A18, A34, A36, A38, A40, A42, A50, A52, A54, A58, A62</td>
</tr>
</tbody>
</table>

All of the optimal combinations of curing measures in Table 7 are combinations of thermal protection measures, including use of thermal curing, insulated coverage and hot concrete. In this case, using higher-strength concrete and indirect curing measures were not among the best choices for the contractors. The selected combinations of measures were determined by characteristics of the project. The case project was located in Sweden, where CO₂ emissions resulting from electricity production are low, which is 0.056 kg CO₂eq/kWh [50]. The low CO₂ emissions associated with the thermal curing and hot concrete casting gave thermal protection measures advantages over use of higher-grade concrete and indirect curing measures. Different combinations will be selected if the developed method is used to evaluate projects elsewhere, e.g., the project analyzed by Turner and Collins [42] in Australia, where emissions of electricity production are 1.35 kg CO₂eq/kWh. Besides project location, the materials used in the project will also affect the results. For example, the case can use cement with lower carbon emissions, like 210 kg CO₂eq/m³ in a study of Collins [49]. This could reduce the advantage of thermal protection over using higher-strength concrete, thereby affecting the selection of optimal curing measures.

The weather conditions during construction of a standard floor will change and influence the optimal curing measures. For example, combination A26, which only upgrades the thermal insulation for slabs, could have provided the lowest CO₂ emissions if construction had started on November 20, 2017 or May 20, 2018. However, the weather during construction would have been colder if it had started on February 20, 2018, and combination A58 (involving not only upgrading insulation for slabs, but also the use of hot concrete for walls) would have resulted in a lower cost than A26. Thus, planning curing measures according to a rule of thumb or using the same measure regardless of the weather changes during construction can reduce construction performance, especially if seasonal weather changes will occur during the project. To maximize the environmental and economic benefits, contractors should thoroughly analyze the weather conditions and carefully select the curing measures for each cast concrete element.

A comparison of the original curing measure combination (A1) and the best measures selected by the proposed method in terms of duration, cost, and CO₂ emissions illustrates the effectiveness of the proposed method, as shown in Table 8. The improvement percentage of the best curing measures
compared to A1 is also presented. Since there are multiple best curing measures considering multiple construction objectives, A2 was selected as an example in Pareto solutions to be compared with A1. As shown in Table 8, the use of the curing measures selected by the proposed method can provide significant improvements, particularly in terms of curing duration and CO₂ emissions. The improvement in curing cost is relatively low because the renting of heaters was for the total construction duration in the studied case. In a different project where the heaters are rented only for the curing duration, there could be larger improvements in cost. As the weather gets colder, the improvement percentages rise and choosing the right curing measures has stronger effects on the performance parameters. If the contractor selects the measures based on preference on one objective, there can be an inferior performance on other objectives, e.g. A40 has the shortest curing duration with an additional cost compared to A1.

Table 8. Comparison of combination A1 and the best curing measures.

<table>
<thead>
<tr>
<th>Construction Time</th>
<th>Start No.</th>
<th>Curing Duration (h)</th>
<th>Curing-caused CO₂ Emissions (kg CO₂-eq/m²)</th>
<th>Curing Cost (sek/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 20, 2017</td>
<td>A1</td>
<td>135.32</td>
<td>3.75</td>
<td>245.41</td>
</tr>
<tr>
<td></td>
<td>A40</td>
<td>59.64 (~55%)</td>
<td>3.63 (~3.2%)</td>
<td>281.18 (+14.6%)</td>
</tr>
<tr>
<td></td>
<td>A18</td>
<td>98.57 (~27.2%)</td>
<td>1.28 (~65.9%)</td>
<td>220.85 (~10.0%)</td>
</tr>
<tr>
<td></td>
<td>A26</td>
<td>115.21 (~14.9%)</td>
<td>1.33 (~64.5%)</td>
<td>208.70 (~15.0%)</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>83.45 (~38.3%)</td>
<td>1.40 (~62.7%)</td>
<td>231.74 (~5.6%)</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>150.19</td>
<td>4.31</td>
<td>257.05</td>
</tr>
<tr>
<td></td>
<td>A40</td>
<td>60.37 (~59.8%)</td>
<td>3.63 (~15.8%)</td>
<td>281.18 (+9.4%)</td>
</tr>
<tr>
<td>Feb 20, 2018</td>
<td>A18</td>
<td>107.81 (~28.2%)</td>
<td>1.31 (~69.6%)</td>
<td>210.11 (~18.3%)</td>
</tr>
<tr>
<td></td>
<td>A58</td>
<td>78.62 (~47.7%)</td>
<td>2.20 (~49.0%)</td>
<td>210.06 (~18.3%)</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>86.36 (~42.5%)</td>
<td>1.41 (~67.3%)</td>
<td>231.74 (~9.8%)</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>117.59</td>
<td>3.01</td>
<td>245.41</td>
</tr>
<tr>
<td></td>
<td>A40</td>
<td>55.32 (~53.0%)</td>
<td>3.40 (+13.0%)</td>
<td>250.33 (+2.0%)</td>
</tr>
<tr>
<td>May 20, 2018</td>
<td>A26</td>
<td>100.22 (~14.8%)</td>
<td>1.29 (~57.1%)</td>
<td>208.70 (~15.0%)</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>81.67 (~30.5%)</td>
<td>1.38 (~54.2%)</td>
<td>231.74 (~4.3%)</td>
</tr>
</tbody>
</table>

Note: *The percentage improvement provided by the best curing measures compared to A1, calculated from \( (P_{meas} - P_{AI}) / P_{AI} \), where \( P_{meas} \) and \( P_{AI} \) denote the performance associated with curing measure combinations \( A_n \) and A1, respectively.

7. Conclusion and Future Studies

In many regions around the world, concrete structures are constructed in cold weather for several months in a year. To protect concrete from cold weather during the hardening process, curing measures are used, including thermal curing, hot concrete casting, adding insulation, the use of higher-grade concrete, and indirect curing measures. To maximize the sustainability and financial benefits, contractors need to thoroughly analyze the weather conditions and decide the appropriate curing measures to protect the concrete during the hardening process. However, there is still a lack of efficient decision support tools for selecting appropriate curing measures considering the temperature conditions and their effects on construction performance. The presented study addressed this lack by developing a Modeling-Automation-Decision Support framework and a prototype combined of several software to help contractors select optimal curing measures in terms of duration, cost, and CO₂ emissions in the prevailing temperatures. The MADS combines a concrete maturity analysis (CMA) tool, a discrete event simulation (DES), and a decision support module to select the best curing measures. Results of its application in a Swedish case study show that selecting Pareto optimal combinations of curing measures proposed by the developed method can provide significant improvements in the considered performance parameters.

A case study was conducted by applying the developed prototype to provide decision support. The results show the proposed method can improve the construction performance caused by curing from the perspective of one objective or all three objectives. For the studied case, significant
improvement was achieved using the proposed method, especially by decreasing curing duration (decreasing 59.8% at most) and reducing curing causing CO₂ emissions (reducing 69.6% at most). The case study also indicated the impact of weather on the selection of curing measures. To maximize environmental and economic benefits, contractors should thoroughly analyze the weather conditions and carefully select the curing measures for each cast concrete element.

The main contribution of this research is the proposed method for evaluating the effects of various concrete curing measures on project performance parameters (time, cost, and carbon emissions) by integrating DES and CMA. In this method (and prototype software) the mechanical properties of concrete estimated by the Maturity Method were connected to construction performance, and the effects of both prevailing weather and interactions between construction activities on inputs for the Maturity Method were considered.

The proposed method has some limitations that should be mentioned. The proposed method is designed for short-term decisions that have a high requirement for data. The results depended on the CMA software used and local weather data provided by the Swedish Meteorological and Hydrological Institute. However, the weather at the project site may differ from the weather observed by nearest local weather station. Thus, recording and predicting the weather at the project site could improve the accuracy of the proposed method. In addition, the limitations of the CMA analysis will affect the outcome. For example, the maturity database of the CMA tool was based on information on concrete products of several specific concrete producers, and the maturity data may differ from products of other producers. If the data are not able to be obtained, the method is not applicable. The proposed method also only considers the direct effects of the curing measures on construction performance. Some indirect impacts, such as possible changes in workers’ efficiency caused by indirect curing measures, are ignored. These limitations will be addressed in future studies.

**Author Contributions:** Conceptualization, S.C. and W.L.; methodology, S.C., W.L. and T.O.; software, T.O. and M.D.; validation, S.C. and W.L.; formal analysis, S.C. and K.F.; investigation, M.E.; resources, J.N. and Y.W.; data curation, J.N. and M.E.; writing—original draft preparation, S.C. and W.L.; writing—review and editing, K.F., J.N., T.O., M.D. and W.L.; supervision, W.L. and Y.W.; project administration, W.L.; funding acquisition, W.L. and Y.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Key Research and Development Program of China, grand number 2016YFC0701904, the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas), and the Swedish Foundation for International Cooperation in Research and Higher Education (STINT).

**Conflicts of Interest:** The authors declare no conflicts of interest.

**References**

3. European Ready Mixed Concrete Organization (ERMCO) Ready-Mixed Concrete Industry Statistics (2017); European Ready Mixed Concrete Organization (ERMCO): Bruxelles, Belgium, 2017;
4. American Concrete Institute (ACI) Standard specification for cold weather concreting (ACI 306); American Concrete Institute (ACI): Farmington Hill, MI, USA, 2002;
7. Swedish Meteorological and Hydrological Institute (SMHI) 250 Years of Weather Observations at the Stockholm Observatory; Swedish Meteorological and Hydrological Institute (SMHI): Norrkoping, Sweden, 2006;
8. yr.no Weather statistics for Luleå, Norrbotten (Sweden) Available online: https://www.yr.no/sted/Sverige/Norrbotten/Lule%C3%A5/statistikk.html (accessed on April 5th, 2020).
10. yr.no Weather statistics for Heidelberg, Baden-Württemberg (Germany) Available online: https://www.yr.no/place/Germany/Baden-W%C3%BCrttemberg/Heidelberg/statistics.html (accessed on April 5th, 2020).


47. Cementa AB *Environmental Product Declaration: Portland Fly Ash Cement CEM II/A-V 52.5 N (Bascement); Cementa AB: Heidelberg, 2014;

48. Angervall, T.; Flysjö, A.; Mattsson, B. Jämförelse av dricksvatten-översiktlig livscykelnalys(LCA); The swedish institute for food and biotechnology (SIK), 2004;


50. Itten, R.; Frischknecht, R.; Stucki, M. *Life Cycle Inventories of Electricity Mixes and Grid; Paul Scherrer Institut (PSI), Villigen, Switzerland, 2014;


52. European Federation of Concrete Admixtures Associations (EFCA) *EFCA Environmental declaration - plasticizing admixtures; European Federation of Concrete Admixtures Associations (EFCA): Minneapolis, MN, USA, 2006;


© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).