The Weather Ledger

May 2021

A practical demonstration of distributed ledger technology (DLT) and internet of things (IoT) in construction.

Abstract

Having identified a critical pain point for the construction sector, the Weather Ledger aimed to minimise the administrative burden and (non-intuitive) subjectivity in making weather compensation event claims. Following a trial in real-world environments, this paper aims to share insights to demonstrate how the combination of internet of things (IoT) and distributed ledger technology (DLT) underpinning the Weather Ledger pilot has streamlined legal proceedings, reduced back office tasks and provided objectivity and trust to compensation events.

Executive summary

The Weather Ledger project was born out of a concern for the current position of the construction industry, with the knowledge that appropriate digitisation has a beneficial impact on profitability and the desire to see a technology innovator bring radical transformation to digitised industries.

This consortium project, funded by Innovate UK, provided the opportunity to explore the potential benefits of using advanced digital technologies to provide accurate and timely weather data. This is a critical requirement for determining weather-related compensation claims, managing adverse weather conditions and lessening the impact of one-in-10 year weather events.

The report examines the practical application of distributed ledger technology (DLT) and the internet of things (IoT) in the construction industry.

The paper will highlight three main areas:

1. The key benefits and impact of deployment of the Weather Ledger trial, capturing the overall value of decentralised, distributed systems, with the creation of cost savings and time saved on various onerous tasks.
2. How this trial was undertaken, including an implementation roadmap for replicable success, which could extend to other DLT and smart contract use cases.
3. Considerations for policy and decision makers to lower the barriers to entry for construction companies who wish to adopt similar advanced technology stacks.

Despite a few challenges on the journey, the team successfully developed a full-stack solution incorporating internet of things and distributed ledger technology and smart legal contracts, gaining useful insights from a trial period of real-world deployment.

Key findings

1. The data collected from participants in the study demonstrated that the tool had clear benefits to its users
2. Weather Ledgers improve the transparency and trust of weather data
3. The Weather Ledger’s integration of weather data improved productivity, informed project planning and assisted the rescheduling of tasks

Key innovations

The consortium delivered several highly innovative elements, including:

1. Deploying the first full-stack LoRaWAN sensor solution on a construction site
2. Pioneering effective smart legal contracts (SLCs)
3. Multiparty signing of smart legal contracts across all contracting parties

Contents

Introduction

Digital Catapult provided distributed ledger technology and internet of things expertise to create a framework of standards for the Weather Ledger, an Innovate UK project. This project demonstrated the benefits of developing this technology for use in the construction industry.

The UK construction sector is in crisis.

The most recent full-year statistics from the ONS show that in 2019[1], construction had seen five years of steady decline in new orders for all work, with a contraction in the number of registered firms and the largest number of insolvencies among any sector of industry. This was compounded by five years of falling employment in the sector, and the slowest rate of wage growth across all UK industry despite increasing prices for project delivery. Among the top 100 contractors at the time, the average profit margin was just 1.5%[2].

The COVID pandemic of 2020 shocked the industry with an immediate 40% downturn in growth, and even at the end of the year, new work remained 3% below its pre-pandemic level.

The construction sector accounts for:
6% of the UK economy
8% of the UK workforce[2]
13% of all registered businesses[1]

The sector currently accounts for 6% of the UK economy, 8% of the UK workforce[2] and 13% of all registered businesses[3] – with a large skew to the long tail of micro- or single-operator entities. It should be a powerhouse of productivity, meeting the surge in demand for more housing and modern, world-leading infrastructure. Yet it remains the UK's least productive sector, and has been since 2008[1].

Not surprisingly, construction is one of the UK's least digitised industries, just ahead of agriculture and hunting[4]. Chronic under-investment, low margins, and the predominance of independent small to micro-scale businesses make the broad uptake of digital innovation a difficult proposition.

The construction industry must actively embrace digitisation if it hopes to cut costs, retain workers, and improve overall productivity. A late 2019 report[5] from the construction industry consultancy Causeway found that over half of those surveyed were restricted from investing in modernising due to low margins. However, up to 90% of those that did overcome this barrier realised up to 20% reductions in operating costs through supply-chain and billing optimisation, while increasing employee productivity and retention.

Automating compensation

The Weather Ledger project was born out of a concern for the current state of the construction industry, with the knowledge that appropriate digitisation has a beneficial impact on profitability and a desire to see a technology innovator bring radical transformation into the sector.

There are many potential opportunities for such digital transformation, but this project narrowed down to one small, and often overlooked, opportunity to demonstrate the application of cutting-edge technology to an industry challenge.

Discussions with industry revealed that managing contractually-agreed compensation events (CEs) is not as straightforward as it should be. These often require lengthy periods of evidence collection and compilation, documentation and the prolonged involvement of site staff and project management. This becomes all the more arduous if a CE is disputed, wherein legal teams or third party adjudicators must be brought in to the process.

Regarding the focus of this particular project, while disputes related to adverse weather constitute only around 5% of all CEs, this is unacceptably burdensome for events that should be binary. This translates into potential lost hours of productivity, with knock-on effects for project delivery and overall profitability.

The core problem is that contractually-relevant one-in-10 year weather conditions happen surprisingly often. That said, contractors and subcontractors do not always have the necessary evidence to prove that they are eligible for a compensation event. In too many cases, the authorised Met Office weather station is located too far away to accurately record conditions on site.

The primary goal of this project was to therefore build a solution that would:

- Provide trusted ultra-local weather data
- Automate the detection of weather-based compensation events
- Make an adjudication
- Notify parties of the contractual implications
- Prevent disputes and recover labour

While this proposition would initially appear to be straightforward or even trivial in scope, every step from conception to implementation and real-world testing has raised new challenges and insights that are important to share with the wider community.

Project conception

This project originated from work undertaken by Digital Catapult to explore the specific opportunities for deploying distributed ledger technology in the construction sector at the end of 2018. These explorations took the form of a set of collaborative workshops and challenge framing exercises termed 'DLT Field Lab'.

As the UK's leading digital innovation agency, Digital Catapult's remit is to enhance the UK's economy through the appropriate uptake of advanced digital technologies[1], including internet of things and distributed systems (covering DLT and blockchain).

The internet of things proposes a future where we can gather much richer and more useful data from our environment, and use this to improve processes and behaviours.

One of the key attributes of LPWAN (low-power wide area networking) technology is the fact that devices and sensors require very little power and can be run from batteries for durations up to several years with tuned optimisation. This makes the technology ideal for use cases that require remote sensors without constant and reliable power sources. The frequencies and transmission protocols utilised by LPWAN solutions are well suited for deep in-building and underground coverage and operate effectively over long distances and through challenging radio conditions.

At present there are a number of competing LPWAN and traditional cellular technologies, each with particular strengths and drawbacks. These are:

- LoRa
- Sigfox
- Narrow-Band IoT (NBIoT)
- GSM (mobile) radio - 2G, 3G, 4G
- 5G

Selecting the appropriate IoT stack, combining sensor, radio, power, protocol, and embodiment is highly dependent on the use case and requires careful consideration.

DLT has captured the attention of both industry and the general public over the past decade in the form of blockchain and the potential of autonomous software programmes that operate in a trustless fashion on shared data termed smart contracts. Setting aside the how of blockchain/DLT, at its core this technology can coordinate multiple independent stakeholders in a direct peer-to-peer manner without reliance on intermediaries or third parties, to enable trusted data exchange and verification.

This approach could dramatically improve the fundamental coordination challenges that underlie a multi-stakeholder construction project. But as a radical proposition, DLT faces many hurdles to widespread adoption, particularly in an under-digitised sector such as construction. These include:

- Misunderstandings and misconceptions
- Technological instability
- Lack of visible deployments
- Absence of transparent deployment case studies
- Absence of information on business uplift or ROI

To overcome these hurdles, the DLT Field Lab brought together a diverse group of construction primes and major clients with the critical addition of a selection of highly innovative startups specialising in blockchain and DLT. Over two half-day sessions, the purpose was to discover shared, seemingly intractable, multi-party, coordination challenges that occur in the normal flow of a construction project.

With industry experts providing insights into these challenges through their knowledge and experience, the innovator community had the opportunity to reflect upon these challenges and map them against their practical understanding of state-of-the-art DLT.

Of the handful of challenges that emerged from initial screening[2], the most opportune and addressable in the near term was overcoming inter-party frictions and the knowledge imbalance in handling weather-related compensation events.

Project conception

In the months that followed these discussions, the project team behind the Weather Ledger naturally emerged from a collection of interested parties engaged in broader discussions around digital transformation in the construction sector.

Each partner to the project brought valuable skills and experience to bear throughout.

Innovate UK grant funding

Due to the difficulty in obtaining industry funding to undertake these types of high-risk technology R&D activities, a project proposal was submitted to the Transforming UK Construction round 2: MMC, digital and whole life performance call from Innovate UK[3] in October 2019. This had a total project cost of £588,733, and a request for subsidy in the amount of £414,039 (70%), with the following breakdown per partner:

Ehabitation: £173,590

Clyde & Co: £69,828

Bam Nuttall: £112,588

Ferrovial: £62,819

Connected Places Catapult: £80,192

Digital Catapult: £89,716

The project was successfully granted and commenced in April 2020.

Digital Catapult
Brought deep technical expertise and existing tooling in the two advanced digital technologies (DLT and IoT) being developed by Ehabitation to facilitate their deployment.

Ehabitation
Highly innovative startup. Brought skills and experience in the construction industry, digital project management, and Distributed Ledger Technology.

Connected Places Catapult
Provided skills, expertise and connections across the construction sector to explore standardisation and enhance uptake of learnings from within the project.

Bam Nuttall
Major UK construction company with £770m revenue and 3,000 employees in 2019. Provided sector knowledge and a willingness to engage in innovative R&D, providing testbeds for real-world deployment at Dawlish and Stubbington.

Ferrovial
Major European construction company headquartered in Spain. Revenues of Û6.341 billion and 80,119 employees in 2020. Provided further practical insights to shape the final solution and offered a separate real-world trial environment in HS2.

Clyde & Co
Deep experience in construction law. Actively engaged in the Accord Project, seeking to open the future of legally compliant smart contracts.

Technical implementation

Eliciting and capturing DLT requirements

Building a software application that relies upon distributed ledger technology to arrive at a shared state of events between disparate stakeholders comes with unique challenges.

Unlike traditional software engineering which focuses on a single organisation, requirements for a decentralised application must be elicited from all potential participants in the network, including intended end-users from each of these organisations.

The project followed an Agile approach to software development after initial requirements were gathered in field surveys, stakeholder meetings and design thinking workshops. These requirements offered a clearer understanding of the multiple aspects to be delivered and refine the initial vision for the system.

Field surveys involved a series of interviews conducted with 10 end-users who worked on construction sites and were most likely to use the Weather Ledger tool. These on-site staff gave valuable insights into the pain points they faced in dealing with weather related compensation claims on a daily and project basis. Usability issues such as device types (desktop/mobile) and network connectivity were explored and noted.

Stakeholder meetings were held with each of the consortium partners (BAM Nuttall, Ferrovial and Clyde & Co) to gather views on the features and functionality that the Weather Ledger should support, specifically those related to their current and expected business processes and workflows. These meetings also explored the technical parameters in selecting suitable weather stations, NEC clause structure for the legal smart contract and thresholds for compensation events.

Digital Catapult conducted Design Thinking Workshops to synthesise and structure the previous findings from both the field surveys and stakeholder meetings. The outcome was a clear description of stakeholder views and requirements, with a projection of value creation (Appendix A). A critical outcome of deploying of the Weather Ledger is notification of various events (for example weather forecast, compensation etc.) and raising these at the right level based on the roles and responsibilities of particular end-users. The design thinking workshop helped to untangle and clarify this aspect for the technical partner Ehab to implement (Appendix B).

High-level Technical Architecture

The architecture of the Weather Ledger system is illustrated below:

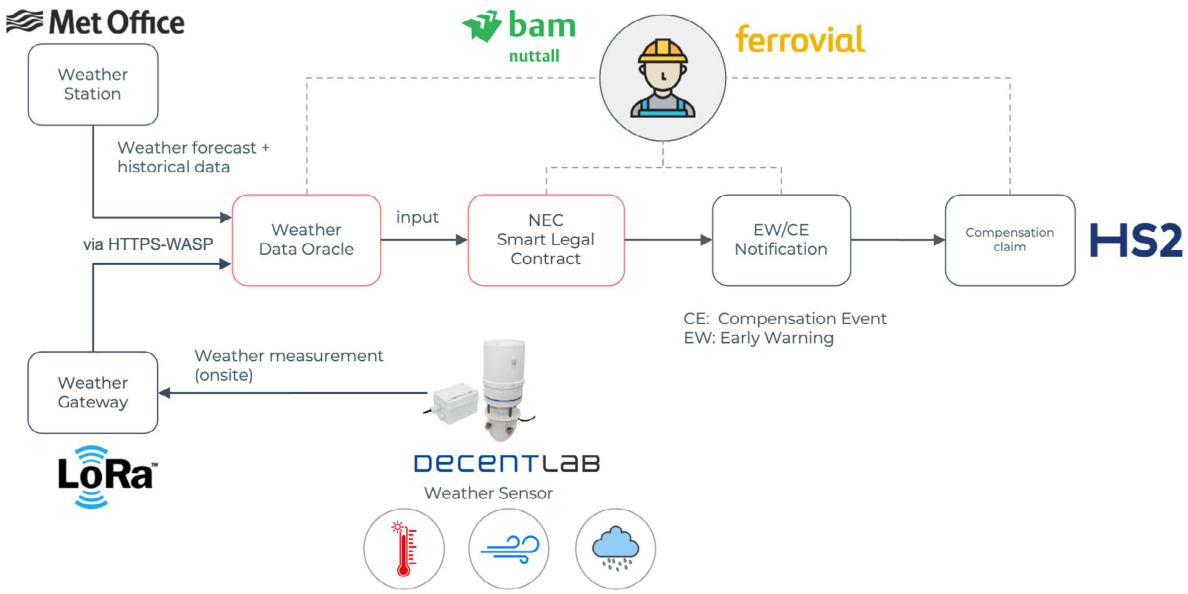


Figure 1.The architecture of the Weather Ledger system.

The Weather Ledger architecture consists of the following components:

IoT weather sensor (DecentLab Weather Station[4])
Captures eleven weather parameters. The most relevant ones are - air temperature, barometric pressure, rainfall (precipitation), wind speed, wind direction and wind gusts.

IoT gateway
Weather data captured from the sensor is passed to a sensor gateway that connects to a public/private communication network to transmit the data to the back end platform that supports the Weather Ledger software tool. LoRaWAN was selected as the technology to be deployed, which has a wireless transmission range of up to 10km.

TTN & WASP data network: The Things Network or TTN[5]
A secure IoT backbone network that provides data endpoints for applications to access data transmitted from an IoT sensor through an IoT gateway. Since any weather data obtained from the sensor and routed through TTN is in raw format and not cached or stored locally, application specific data transformations (converting bytes into weather measurements) were performed using Digital Catapult's WASP service. This is a set of software tooling built by Digital Catapult to enable rapid deployment of prototype IoT services, which was very appropriate for this project. The WASP service also provided local data caching to minimise data loss.

Weather data oracle
Weather data sources are oraclised[6] for use within smart contracts.

Smart legal contract
Smart contracts are programmes that execute on a distributed ledger using data within the ledger so that outputs are highly deterministic and auditable. In this project, part of the challenge was to reinterpret key clauses of the NEC suite into legally-enforceable smart contracts.

Notification of early warning/ compensation event
If predetermined weather thresholds have been reached or exceeded, a notification is sent to appropriate parties.

Compensation claim
After a compensation event is checked and verified, a compensation claim is raised with the client.

Construction companies traditionally rely upon the Met Office for weather reporting and calculation and this project was no different. The construction companies and their clients used the Met Office as a data source for historic data and calculating one-in-10 year events. The data was therefore oraclised from the Met Office similar to the hyperlocal weather data produced by weather sensors, and used to calibrate the one-in-10 year events required by the smart legal contracts.

The development of data oraclisation and smart legal contracts were the critical challenges addressed in the Weather Ledger project from a software engineering perspective. These are described in further detail in the following sections.

Introduction to smart legal contracts

Smart legal contracts are software programs deployed on a distributed ledger (DLT) or blockchain-based system to facilitate transactions that alter or change the state of the ledger.

There have been previous attempts to bridge the divide between precise and deterministic machine-interpretable software programs and human-interpretable legal clauses in paper contracts, but these proved to be both contentious and unacceptable. This is because solicitors who frame contracts cannot be expected to be experts reading software programs and vice-versa. However, both sides agree that the outcomes of contract and software execution should be deterministic.

Recent advances in smart legal contracts (SLC) based upon DLT address this critical problem. SLCs are attractive because they not only automate contractual clauses but also tightly couple legal text to the software code in deployment. Distributed ledgers provide a means of regularising smart legal contract deployment and execution, with provable visible state history accessible to all parties who require it.

A high-level architecture of a SLC is shown below in Figure 2.

SLCs consist of a template and the data that initialises it. The smart contract template is made up of clause text (legal text in natural language), a data model (entities that model objects in the physical world) and logic (business logic codified as computer program code).

One of the advantages of SLC is that these three components are interwoven and tightly coupled in such a way that they are inseparable when deployed in production. The template on its own is an empty shell which comes into force when instantiated with contract data. Together a smart contract template and its data make a complete SLC when compiled and run.

A SLC can be executed in a dedicated execution environment called an Engine, or if the business logic is implemented as a regular smart contract, it can be deployed and executed on a more generic DLT/Blockchain. The tight coupling between the model, text, and code can still be enforced through the formalisation of the distributed ledger.

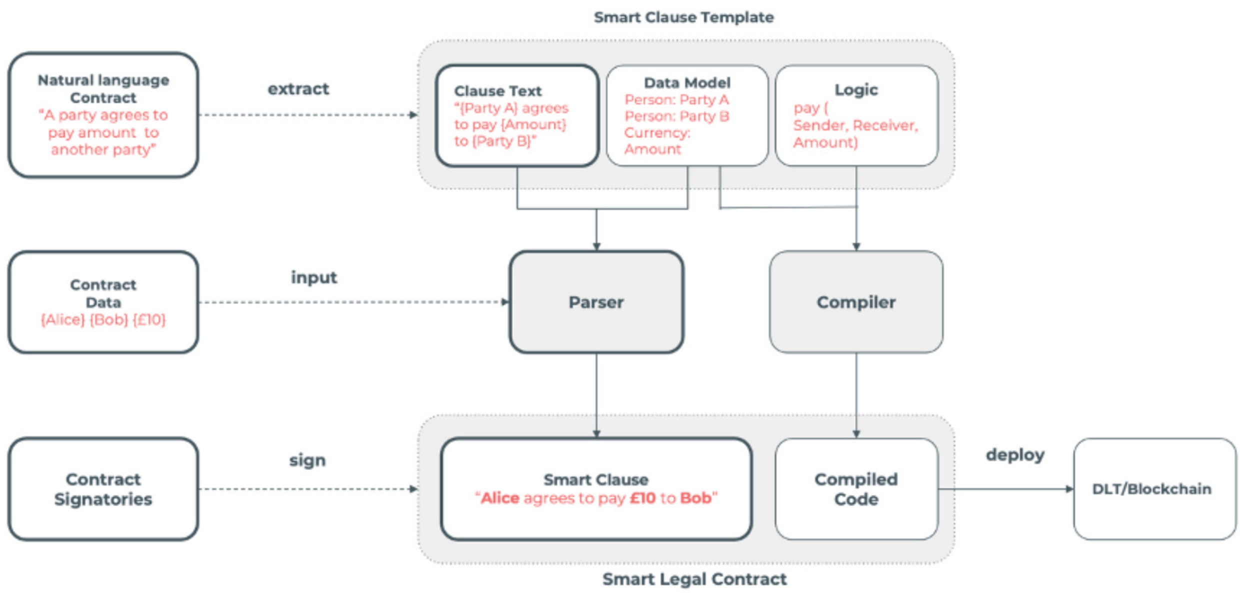


Figure 2. Architecture of a smart legal contract

Selecting an appropriate SLC framework

To choose an appropriate SLC framework to implement the NEC clauses identified as relevant for weather-related compensation, a set of desired features (based on BSI/ISO Standard PAS 333) were considered for comparison and selection. These were the:

- **Clause text:** a representation of a human readable clause taken from legal contract
- **Concepts or models:** variables or concept types contained within clauses
- **Logic:** programmable conditions extracted and referred to from clauses
- **Editor and parser:** combine template with data into draft agreement
- **Digital identity and signatures:** draft agreement is signed into smart legal contract
- **Execution engine:** an environment to execute the smart legal contract
- **Oracle:** mechanism to ingest external data into smart contracts at when executing

There were at least three main SLC options for deploying these features, all of which are Open Source: R3 Corda[7], OpenLaw[8] and The Accord Project[9].

In Corda, the approach is rather simple: a contract or legal text is simply attached to or referenced by a regular smart contract.[10] OpenLaw and Accord instead provide a tighter binding between the legal text, models and business logic.

Figure 3 contains a visual representation of these smart legal contract framework options.

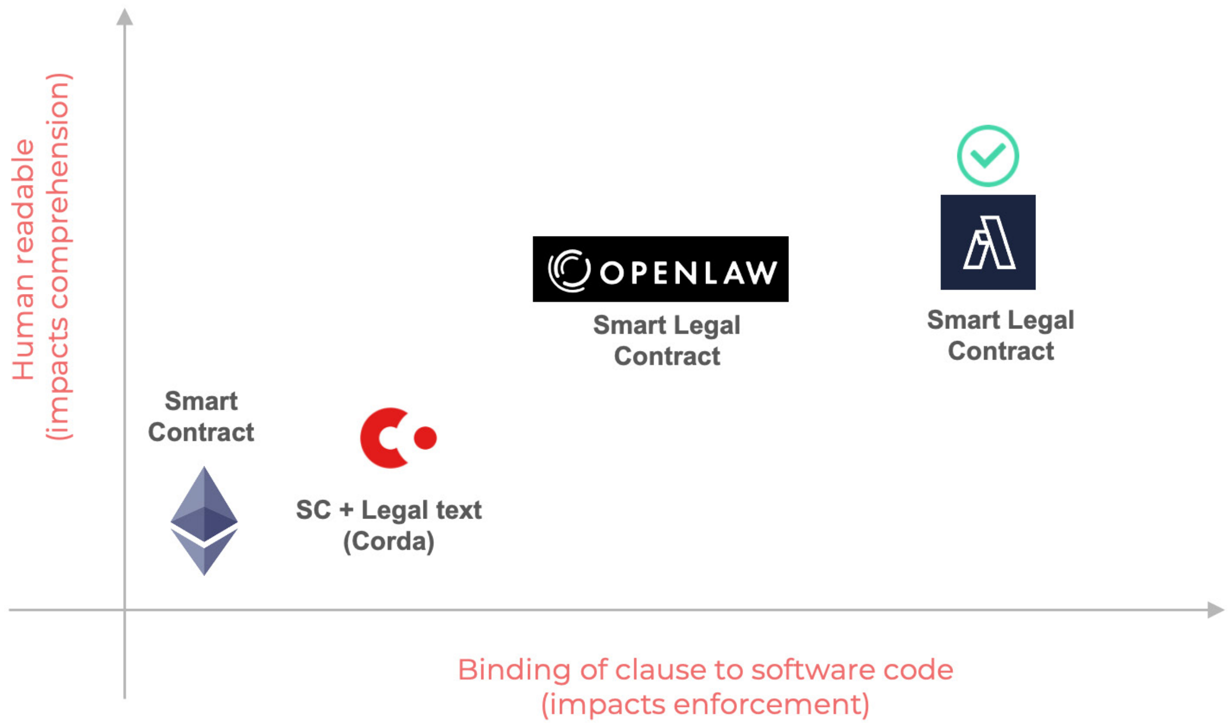


Figure 3. Options for deploying smart legal contracts (as of March 2021)

A comparison of OpenLaw and Accord is described below in Table 1. Accord was found to be a better choice for implementing the Weather Ledger because it offered the following advantages:

- Technically mature components (composer, parser, engine)
- Better architecture and design (integration of legal text, entity model, business logic)
- Better facilities for composing and modelling SLC (IDE plugin and tooling)
- Tighter binding between smart contract code and legal text/clause
- Portable and DLT agnostic (reduces risk)
- Large and active user community (21,167 members, useful for bug fixing and new features)

Table 1. A feature comparison of smart legal contract frameworks.

	OpenLaw	Accord
Clause text (human readable)	OpenLaw markup language	Cicero markup language
Concepts / models	Types and variables in OL language	Types and variables in OL language
Logic	Ethereum / Solidity	Concerto schema language
Template library	https://www.lawinsider.com/tags	https://templates.accordproject.org/
Digital identity & signatures	Blockchain (Ethereum) based	Electronic signature - Docusign
Editor and parser	Online	Online https://studio.accordproject.org/
Execution engine	Nodejs	Nodejs
DLT support	**Ethereum** (via SC reference)	**HL Fabric, R3 Corda**

Oraclising weather data

Any smart legal contract developed for the Weather Ledger critically relies on three types of weather data:

1. Historical 10-year weather data from the Met Office
2. Weather forecasts from the Met Office and other third parties
3. Live weather measurements on-site using a hyperlocal IoT-enabled weather station

As financial (or other) compensation and early warning events are computed from these, it's important to ensure that data obtained from any sources external to the smart legal contract are not only reliable and accurate, but also immutable and resistant to manipulation and misuse. Only in this way can trust be established in the process and thereby the system.

As previously stated, DLT-based smart contracts require external data to be deterministic in order to achieve consensus. This is facilitated through a data wrapping process termed data oraclisation. For the Weather Ledger, two third party oraclisation services called ChainLink[11] and Provable[12] were considered. A side-by-side comparison of these two options is described in Table 2.

Table 2. A comparison of options for oraclisation.

	OpenLaw	Accord
Decentralised service	Yes	Yes
DLT/Blockchain agnostic	Yes	Yes
Available adapters	Ethereum	Ethereum, Rootstock, **R3 Corda, HL Fabric,** EOS
Service type	Trusted intermediary	Untrusted intermediary
Authenticity proofs	n/a	TLSNotary, Android, Ledger

Provable was selected as it supported both Hyperledger Fabric and R3 Corda which were the DLT platforms supported by the Accord SLC framework.

Final technology stack

The final Weather Ledger architecture was implemented using a combination of:

- **Hyperledger Fabric** as the DLT for data consensus and smart contract execution
- **The Accord Project** to provide the SLC framework and wrapper
- **Provable** to oraclise incoming weather data from both the Met Office and the IoT weather station
- ***WASP*** to cache and interpret the IoT weather station data
- **The Things Network** as the IoT data backbone relaying data from the gateway
- **LoRaWAN** as the interlink technology, providing superior transmission distance and longevity for this application
- **The Decent Labs** weather station as the IoT weather station deployed on site

See Appendix D for screenshots on the mobile app and desktop version of Weather Ledger.

The next section describes validation methods to confirm the system requirements were correct and if the features implemented by the DLT/SLC in the Weather Ledger satisfied the needs of the end-users and stakeholders.

System validation – qualitative study

In the final quarter of the project, a qualitative study was conducted with an aim to validate the DLT and SLC aspects of the Weather Ledger. The initial requirements are described in Table 3 below. The study was designed by Digital Catapult and Connected Places Catapult, operating from sites provided by Bam Nuttall and Ferrovial.

Table 3: Initial functional requirement for the Weather Ledger

ID	OpenLaw	Accord
R1	Onboard users and companies	
R2	Set user roles and permissions for data privacy	Shared view of data
R3	Setup and connect to (on-site) weather data source	Data oracle
R4	Setup, configure parameters for Early Warning events (EW)	Smart legal contract
R5	Setup, configure parameters for Compensation Events (CW)	Smart legal contract
R6	Generate EW and CE reports for users	Smart legal contract + shared view of data
R7	Assist user to capture impact assessments of EW/CE	
R8	Enable users to raise CE	

The study also validated whether the software tool was the right one for the application, and in particular to answer difficult questions such as:

- Were the weather parameters chosen for implementation in software sufficient to address user needs on-site?
- Did the Weather Ledger address the needs of end-users when raising EWs and CEs?
- Did the use of a distributed ledger enhance data sharing and did this improve trust?

The initial division into two data collection phases was a practical consideration to provide the opportunity to undertake an interim assessment of user participation, with the data quality and quantity arising from the study. This could allow the team to modify the methodology if there were any anticipated shortcomings.

However, the study progressed smoothly and without any procedural issues. As a result, it was possible to obtain rich data without any need to recalibrate the approach taken. In practice therefore, there was no difference between the first and the second phases of the trial.

Based upon the quality of feedback provided and the nature of events recorded, a select number of participants in the initial phases were chosen for additional contextual interviews where specific episodes were unpacked, and their responses in relation to the environmental and operational context were studied in-depth.

The last two phases of the study were the data analysis phase, spanning two weeks, then a report writing phase spanning another two weeks, producing this report as the final project deliverable.

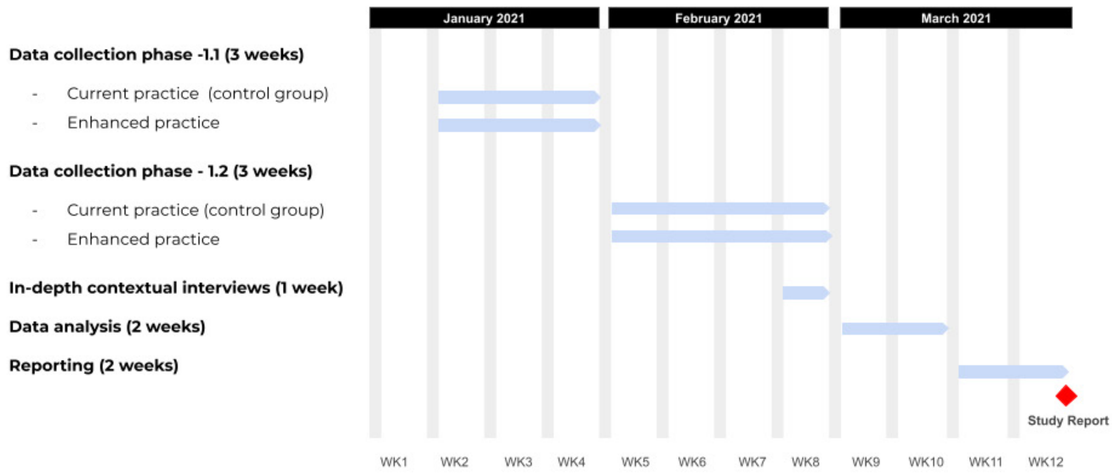


Figure 4. Validation Study Plan

Site Locations

For the study, participants were taken from three construction sites where hyperlocal IoT weather stations were deployed.

1. Dawlish

Project: Reconstructing a critical sea wall
Estimate: £27m | Duration: 12 months
Contractor: BAM Nuttall
Client: Network Rail

In 2014 the Dawlish sea wall collapsed resulting in line closures for nearly three months, significantly impacting the South West economy. The rail track running alongside the sea wall is an essential artery for passengers and freight and it is frequently subject to disruption by storms and waves overflowing the barriers. These issues will be compounded in future by rising sea-levels and climate change. An important part of the works is the use of a Wavewalker - an eight-legged, self-contained jack-up barge that can operate in tidal conditions that would otherwise require project downtime. Up to 100 members of staff may be working on the site during peak periods.

2. Stubbington Bypass

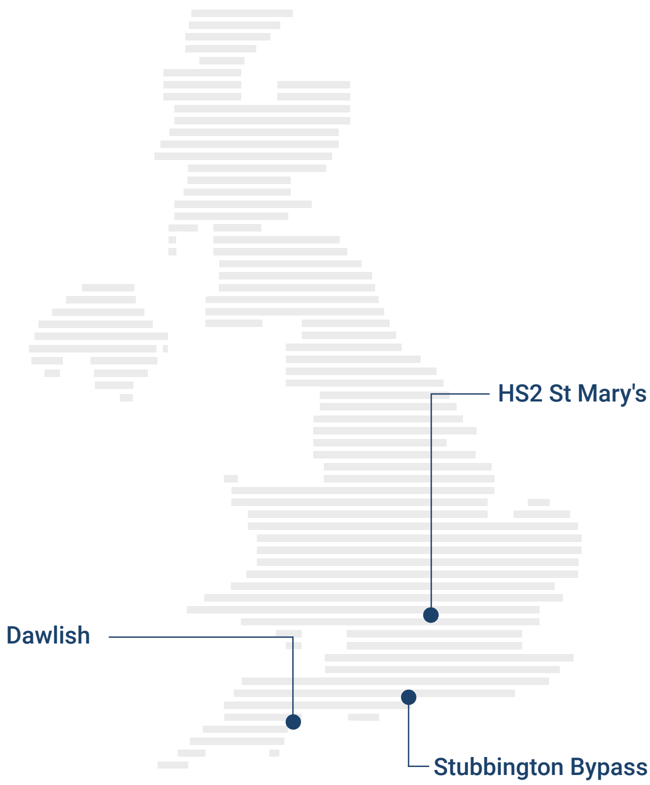
Project: Preparing a 3.5km bypass connection from the B3334 Titchfield Road to B3334 Gosport Road
Estimate: £34.5m | Duration: 12 months
Contractor: BAM Nuttall
Client: Hampshire County Council

Through a variety of traffic management measures and off-road cycle routes, this project aims to divert traffic around Stubbington's north and east sides, improving journey times and reliability on the Gosport Peninsula.

3. HS2 St Mary's

Project: Enabling works on the central section of the 100 km long high speed railway which will join London and Birmingham
Estimate: TBD | Duration: 12 months
Contractor: BAM Nuttall, Ferrovial and Morgan Sindall
Client: HS2

There are two core parts of the project, archaeology and civil engineering.



Study participants

The study involved 15 participants spread across all three sites and divided between two different groups.

The study involved 15 participants spread across these three sites. The participants logged 194 experience sampling entries and provided five contextual interviews over the course of six weeks. These details are shown in Table 4.

Company	Participants	Site location	Roles	Experience Sampling Entries	Contextual Interviews
BAM Nuttall	9	Dawlish, Stubbington Bypass	Foreman, Works Manager, Site Engineer, Sr. Planner, Senior Agent	194	5
Ferrovial	6	HS2 St. Mary's	Project Manager, Sr. Project Engineer, Lead Supervisor		

Table 4. Participant details

The study period divided the participants into two different groups:

- The **as is** or **baseline group** were created to reflect the current practice on the ground
- The **enhanced practice group** used the Weather Ledger tool on a daily basis and studied to measure any observed benefits and value creation over and above baseline practice

This case-control methodology was critical to establish actual differences in behaviour and outcomes when trialling a new software tool.

The two points for head-to-head comparison between the baseline and enhanced practice groups were:

- Time and effort spent identifying, mitigating and reporting weather related compensation claims
- Time and effort spent analysing early warning weather forecasts and taking corrective actions to mitigate its negative impact

Study design: experience sampling and contextual interviews

The study employed two well-established techniques for qualitative data collection: experience sampling and contextual interviews.

Weather Ledger user data was collected using a set of short online questionnaires sent to the participants to collect and record their experiences before and after completing specific tasks; for example when they investigated weather compensation events or responded to early warnings. These experience sampling forms were sent to the participants' mobile phones once a day to ensure they were not overloaded. The questionnaires were designed as an interactive chat application using an online tool called Tripetto[13].

Data collection for both groups was monitored, and user-specific prompts were sent via email and SMS messages to encourage users to participate if they had forgotten or missed sending their feedback regularly.

Using the data collected during initial phases of the study, in-depth contextual interviews were conducted with a subset of participants (five out of 13) to uncover the operational context behind their decisions and actions. In the 60-minute interview, participants were requested to explain their rationale and contextual experience for data they had provided during the data collection phase. The interviews also filled any gaps in knowledge and covered observations not explained before.

Findings and discussion

The data collected from the participants showed that the tool had clear benefits to its users, the most prominent ones are explored here in more detail.

The Weather Ledger improves transparency and trust of weather data

By providing a shared view of data, DLT is often claimed to provide transparency and improve trust among stakeholders. Weather Ledger proved this in reality by providing a singular shared reference point for weather data within the organisation and for external clients. One visible consequence was that it made it easier for contractors and clients to communicate with each other and agree on the same weather data, critical for managing this complex multi-stakeholder relationship.

An additional unexpected benefit was that the shared view of data actually simplified minor tasks such as record keeping (filing on local PC/computer) and streamlined communications between the users.

We discovered that in order to raise compensation claims, site managers would keep meticulous compensation-related weather records from several sources in the form of spreadsheets and electronic documents (PDFs). In the event of a claim, it would take days for centralised commercial teams to collate this data.

The shared view of data enabled by the Weather Ledger improved productivity. Now the data was all in one place, project and site managers no longer needed to maintain multiple simultaneous sets of weather records from several different weather stations and websites as evidence to make a claim.

This shared data simplified the daily task of managing and tracking weather data using spreadsheets, PDFs and bulky email attachments sent between multiple parties. This proved to be a significant improvement for project managers who routinely deal with weather related disruptions and regularly compile evidence. It made their task easier, improving their satisfaction and appreciation when using the tool. From an organisational perspective, improving worker effectiveness and job satisfaction by reducing emails and attachments to streamline record keeping can only be beneficial in human and financial terms.

The Weather Ledger's integration of weather data improves productivity

One of the constant refrains among project managers, site supervisors and planners is the fact that they spend a minimum of half an hour each day trawling through the weather reports from multiple sources to anticipate any disruption to their planned work.

One of the main benefits reported by study participants was that the Weather Ledger dramatically reduced the time and effort required to collect and analyse these reports on an immediate and ongoing basis. According to the site supervisor at Dawlish, "It takes less than five minutes now instead of 30 minutes looking through various websites." Cumulatively, this improved productivity can be translated into monetary savings for construction companies.

For example, if this saving of 30 minutes per day is applied to two sub agents on a site that require the Weather Ledger's services, then the cumulative productivity could add up to 16 person days a year (140 person hours at 8.5 hours per day). Here the secondary effect of reducing emails and phone calls has not been considered, but would have a further positive benefit.

The Weather Ledger improved project planning and rescheduling of tasks

Project managers and site managers received advanced weather reports from Weather Ledger, helping them plan day-to-day project work.

Take for example the site in Dawlish where construction work was carried out along the coast edge using a WaveWalker[14]. This has a hiring cost in the range of £15,000 per day and any cancellation between 0-12 hours would incur a 100% charge, while cancellations between 12-24 hours would be charged at 50%, while cancellations in advance of 24 hours would incur no charge at all. Getting advanced warning on projected wind speeds through the Weather Ledger gave project managers ample time to replan and cancel equipment hire in a timely fashion, thereby reducing their losses due to unfavourable weather conditions. One year of enhanced monitoring by the Weather Ledger could save hundreds of thousands of pounds across an organisation.

Compensation claims for work stoppage due to adverse weather conditions can quickly compound, as construction tasks have complex dependencies. It is not just about cancelling the laying down of concrete, but also cancelling shifts for the workers required on site, rescheduling specialist equipment, and ordering additional equipment for works to be conducted while the concreting is not possible.

As described by one of the site managers at Dawlish, "When the WaveWalker tug was postponed due to weather, we required an additional one-week barge hire. Rescheduled concreting works require further logistical adjustments - undertaking other works to fill the gap, so the project completion date is not affected."

Calculating the impact in monetary terms may not be so straightforward, as a reduction in losses could result from cancelling equipment and paying only partial charges.

Future enhancements

The validation study and other feedback interviews during the project revealed several areas where the system could be further expanded to address specific customer needs for contractors and clients. Some of these are described below:

(i) Sharing data with all DLT network participants

As stated at the outset, building decentralised systems and applications is a highly complex task due to the diverse range of stakeholders who must be accounted for in the solutions. This enlarges the requirement set for a minimum successful deployment. If even one of the proposed network participants is left out of planning considerations, the results can be damaging.

In the Weather Ledger, one client (HS2) was left out of early discovery, so their requirements and views were not taken into consideration. This meant a shared view of the weather data was not visible to them and therefore they could not trust the hyperlocal data and accept it for use in their contracts. This has potential ramifications for this and other projects seeking to develop distributed solutions.

(ii) Smart contract transparency

There were difficulties in presenting the internal workings of the smart contract to the end users. For example, users of the Weather Ledger indicated they did not know why a compensation event notification wasn't received when it should have been and they felt locked out from querying the thresholds of the smart contracts. Moreover, users also wanted to know how the one-in-10-year calculations were internally computed by the smart contract from Met Office data. User trust and confidence in the hyperlocal weather data could be improved by showing the business logic of the smart contract and its threshold variables for executing events.

(iii) Calibrating appropriate notification levels

The validation study showed that some users received either no notifications or excessive notifications. Both cases are likely to annoy users and cause them to lose interest in using the system. A facility to enable users to individually subscribe to specific event notifications should be provided to calibrate the appropriate level of notification required.

(iv) Weather station non-functional requirements

If data obtained from hyperlocal weather stations are to be trusted, then they should be as robust and reliable in collecting weather data as the Met Office. All sub-components that support availability of the weather data such as power sources and wireless network data plans, should be pro-actively monitored programmatically. For example, battery levels in the IoT base station could be remotely monitored through their programming interfaces and displayed to users.

Similarly, weather sensors can be obstructed by debris (purposely or accidentally) or have their vertical position changed by external physical factors. In both cases, readings could be erroneous. Therefore, sensors need to be able to monitor their local context to signal if anything has changed in their setup or physical condition.

(v) Catering for tidal and wave data

Construction projects are highly diverse, with significant differences in challenges and needs. Correspondingly, the equipment used on each site may vary in type and form, as well as the need to account for different weather factors, for example, temperature, rainfall, snow, wind, fog unique to that location. The Weather Ledger needs to take project specific requirements into consideration and allow for the most appropriate site-specific weather coverage. For example, at the Dawlish site, operating specialist equipment like a WaveWalker not only requires wind speed but is crucially dependent on monitoring tidal and wave activity. The Weather Ledger will need to cater to these additional weather data sources and regularly elicit and check if the current weather data satisfies the requirements of ongoing and new projects.

(vi) Integration of project management and weather risk

For project managers using the Weather Ledger, their primary focus is to deliver construction projects on time and within budget. Forecasted or actual weather events cause disruption to these project plans. Weather compensation events need to be monitored, but few result in compensation claims (less than 2%). An appropriate extension of the Weather Ledger would be to augment existing project management tools (for example early warning registers) with weather risks.

Adverse weather conditions contribute to the stoppage of work, resulting in delays and cost overruns. Advanced warnings from the Weather Ledger can inform users of impending weather conditions, but it was realised during the study that this wasn't sufficient on its own, as it depended on the skill of the project manager to assess the impact of adverse weather on the project plan. A next logical step for the Weather Ledger would be to interact with the project plan to compute a daily risk score.

(iii) Immutable site-diary

It is accepted that site diaries have an important role in recording evidence for compensation claims, particularly that they capture project decisions on site. Having an online version of the diary could be useful on its own, but if a site diary is a critical piece of evidence, then it must be resistant to changes and modifications. Keeping diary entries in an immutable state using DLT would be a significant benefit.

Opportunities and challenges

Data-as-a-Service: Hyperlocal weather data

Accurate and timely weather data is a critical requirement for determining weather-related compensation claims.

To enable the collection of hyperlocal weather data, IoT weather sensors were deployed on construction sites. However, this presented its own challenges, which are covered in detail in the report 'Guide to the effective deployment of IoT on construction sites'[6].

In brief, the key challenges to installing a hyperlocal IoT weather service include:

Power

Not all sites had ready connections to constant power, which meant the project relied on setting up solar panels and batteries to power the sensors and IoT gateways. This energy source proved to be unreliable, as the energy captured by the solar panels wasn't sufficiently predictable to continuously power the device for prolonged periods of time spanning weeks to months. The hyperlocal data source had to be correlated with other weather sources to ensure the Weather Ledger was functioning as expected. The key lesson here is to ensure sensors on construction sites have access to a reliable power source - preferably a regular power socket. A future approach could be to integrate IoT LPWAN gateways into other equipment that one would expect to find on a building site such as security cameras, a security gate cabin, or traffic management systems.

Installation and maintenance

Even minor maintenance tasks such as installing the sensor in the correct location or replacing a battery for a sensor gateway can be problematic, as construction workers may not be familiar with the sensor setup to do it themselves.

Device monitoring

IoT weather sensors used for decision-making need to be monitored to ensure they are not physically obstructed by debris, have not been tampered with and report accurate information.

Network access

The IoT gateways used in this project relied on a mobile network to transmit data. This meant that the mobile data plan had to be monitored and updated to ensure the gateways could send their data to TTN and then onwards to the Weather Ledger.

A key takeaway from this project is that managing the life cycle of a hyperlocal weather station is a separate and equally important part of providing a Weather Ledger service to the construction industry.

Trust in hyperlocal weather data

When an NEC contract is signed, it is common practice for the clients to state their source for trusted weather data, which usually defaults to the Met Office.

Assuming a reliable hyperlocal data source is established through installation of IoT weather sensors on a construction site, with the data pipeline secured end-to-end and oraclised, the Weather Ledger data will still be limited in its uptake. This is due to the perception that the Weather Ledger data is not deemed to be on par with the same legal effect as Met Office data. More widespread pilots of the Weather Ledger will be necessary to shift this client perception, to improve trust in hyperlocal weather data, convincing them about the system and its veracity.

Opportunities for standardisation

Reusing NEC clauses

NEC is a de-facto standard in the construction industry. Smart legal contract clauses automated for the Weather Ledger can potentially be reused across other construction projects with relatively minor changes in the contract data. The Weather Ledger project team will aim to release some of these clauses into the public smart legal contract library, maintained by the Accord project, to benefit the wider community worldwide.

Standardisation of roles

One of the challenges in building a decentralised application is that the application has to cater to the roles and permissions of not just one organisation but all those in the network. Enabling a shared and consistent view of data across partners in the consortium will require a mapping of roles and responsibilities from each organisation. This mapping in the form of an industry specific ontology could cover the most common roles, job descriptions and the data access privileges they require.

Identity register of construction companies and clients

For smart legal contracts to have any legal force, they must be digitally signed to capture agreement and acceptance by the contracting parties in a production environment. Enabling digital signatures for organisations and their delegated parties has been an area of active research and development for many years. One potential solution, and a good match for DLT and smart legal contracts, would be a self-sovereign identity register.

Key innovations

Deploying hyperlocal weather stations

Weather Ledger may not be the first project to have deployed a weather station to measure weather data, but it has been the first to deploy a full-stack LoRaWAN sensor solution on a construction site. This solution provided valuable insights into numerous issues that were not anticipated prior to the project. The project also uncovered multiple factors that impacted data quality. More importantly, lessons have been learnt on data sharing across organisations to enable trust.

Pioneering effective smart legal contracts (SLCs)

The popular NEC contract suite was designed for paper-based contracting. Its weather-related compensation clauses are not readily amenable to automation as smart legal contracts. Clyde & Co, a legal firm and one of the consortium partners that specialises in developing smart contracts, played a pivotal role in extracting the legal text and tailoring it to fit into a smart legal contract (law-to-code binding) which was then automated and deployed in production. To make this partial automation of the NEC contract relevant to the rest of the paper-based contract, additional legal text was drafted to be used alongside the main NEC contract (code-to-law binding). Both these innovations make smart legal contracts attractive for other commercial deployments as they address the aspect of making smart legal contracts legally binding.

The Weather Ledger was the first in the UK to successfully implement a smart legal contract in production and the first to partially automate weather clauses from a commercial NEC contract.

Multiparty signing of smart legal contracts

It is not enough that SLCs are deployed on DLT. To have any legal force, the agreement between the contracting parties must be captured in a Certificate of Agreement following current document signing processes. For the Weather Ledger, Digital Catapult developed a detailed architecture using self-sovereign identity technology[2] to enable multiple parties to digitally (cryptographically) sign the smart legal contract (its legal text, model, and business logic) and the contract data. This process is illustrated in Figure 5.

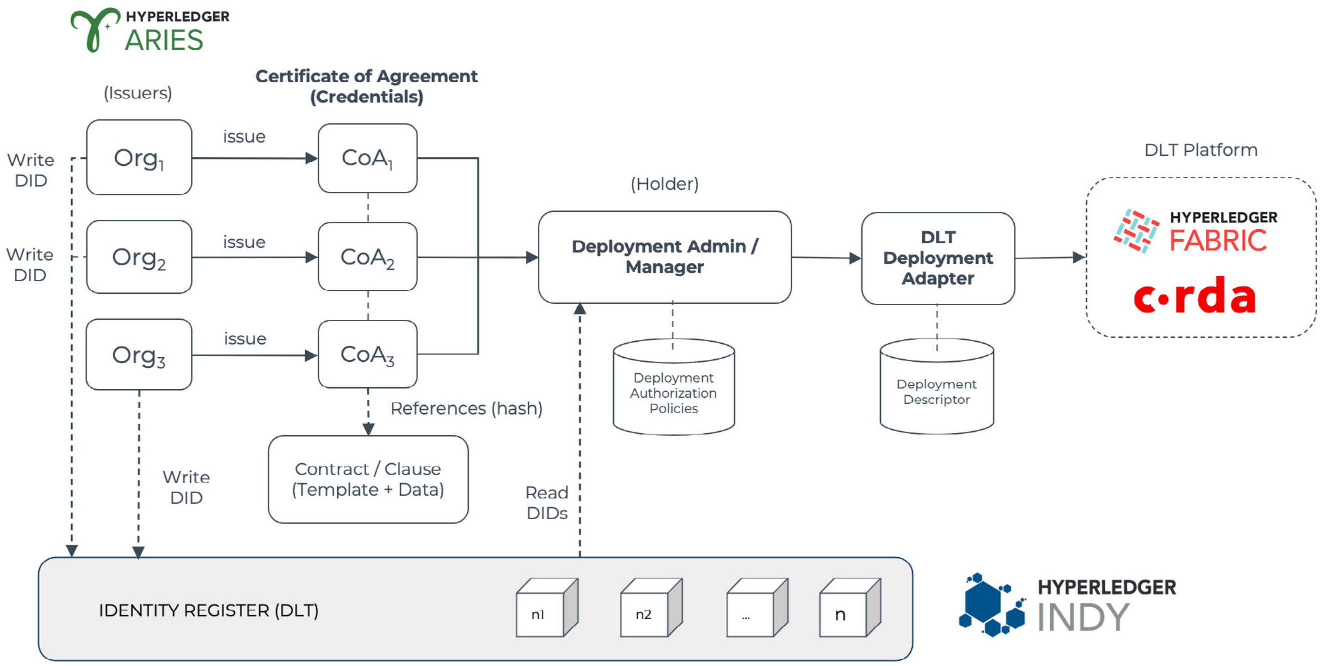


Figure 5. Architecture of multiparty signing for smart legal contracts on Weather Ledger developed by Digital Catapult.

The architecture in Figure 5 consists of four main components: client wallet, identity register, deployment administrator or manager and deployment adapter. Consent and agreement for smart legal contracts are captured in the form of verifiable credentials[15], which can be cryptographically verified on demand, with identities of signatories held in a public identity register (for example Hyperledger Indy).

One of the main benefits of this approach is that a smart legal contract can be digitally signed before it is deployed on a DLT platform. Furthermore, the use of digital signatures ensures that those entities that sign the contract can be tracked back and authenticated, so that their acceptance is recorded in a non-repudiable manner. Finally, any tampering of the deployed smart contract can be easily detected through cryptographic verification.

The downside of this approach is that signatures have to be obtained individually from each organisation or contracting party. However, this has an advantage over techniques where a single private key is split or shared among a group of signatories. If an organisation is involved in multiple smart contracts, then it will have to maintain separate 'partial' or 'shared' keys for each of the contracts it enters into. On the other hand, having a single pair of keys to be re-used multiple times makes this approach easier and more manageable for organisations and users who may not be tech savvy. By issuing a separate certificate of authentication for each signatory, generating proofs (including zero-knowledge proofs) is simpler and easier to verify than a key sharing method.

Considerations and conclusions

This consortium project, funded by Innovate UK, provided the opportunity to explore the benefits of using advanced digital technologies to benefit the strained UK construction sector.

As is always the case with cutting-edge R&D, the team faced a number of challenges along the journey. Nethertheless they successfully developed a full-stack solution incorporating IoT, DLT and smart legal contracts, gaining useful insights from a trial period of real-world deployment.

The consortium delivered several highly innovative elements, not least the smart legal contracts, but also a multi-party signing mechanism based upon self-sovereign identity and the overall trial methodology for experimenting with advanced technology on construction sites.

The trial demonstrated a positive business case for the Weather Ledger, with potentially significant cost savings arising from:

- Improved data transparency and coordination
- Improved productivity
- Improved project planning and scheduling

A number of potential future directions became apparent during the project, including:

- Enhancing the IoT offering in terms of technology (power supply, range of sensors) and deployment
- Integration with project management tooling
- Extending the range of ledger integrations with oraclisation services and legal smart contracts
- Improving digital tooling for signatory management

Arising from these, we ask external parties reading this report to consider the following:

1. It is very difficult to manage highly innovative multi-stakeholder research projects as a startup while simultaneously developing the technology and the company. Some consideration must be made for externalising project management and remaining focused on the goals of the startup. Catapult organisations could adopt this role as a neutral convening party, if grant conditions were favourable.

2. It is critical to break complex technology development projects into a series of manageable discovery, development and deployment phases. Modern software development practices are agile and iterative, which is difficult to capture within the framing of timelines, milestones and the deliverables required of a traditional Innovate UK grant application.

3. Development projects for cutting-edge technological propositions benefit from an integrated in-field trialling period. These must be designed and implemented carefully, using appropriate methodologies.

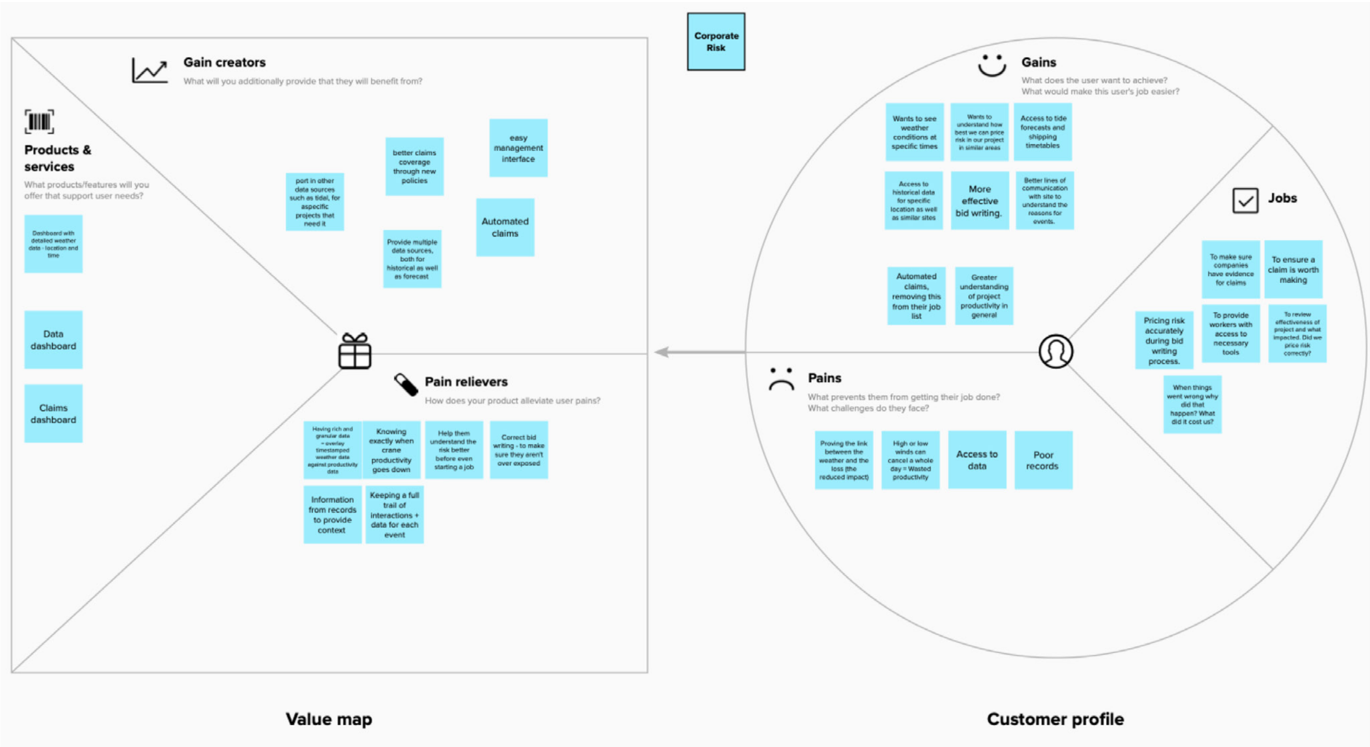
4. The construction sector stands only to gain from embracing digital transformation. Technology is not only built by large traditional suppliers, but also by unique and exciting startups. Construction companies and others must learn how to communicate with and work alongside the smallest innovators if they hope to overcome some of their greatest challenges.

5. There are multiple opportunities for the UK to excel in the field of smart legal contracts if conditions are made favourable for undertaking experimental deployments. This could take place within well-designed real-world trials, or purpose-built sandboxed environments.

6. Graduation from sandboxed environments must be sign-posted from the outset if innovation is to translate into real-world change.

Appendix

Appendix A: Value proposition mapping



Appendix B: Notification and data sharing levels

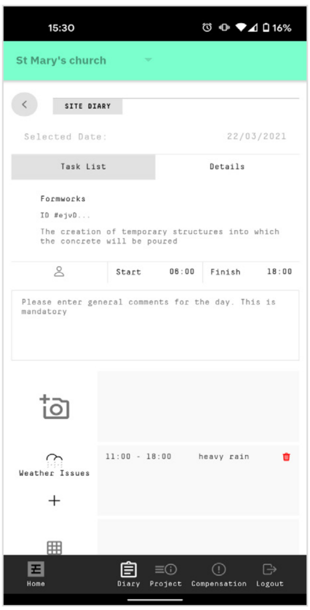
Level	Role	Usage reason	Usage frequency	Warning notifications	Input required
Site	Engineer	Planning, Monitoring	daily	Warnings, EW	Discuss impact, mitigation
	Foreman	Planning, Monitoring	daily	Warnings, EW	Discuss impact, mitigation
	Supervisor	Planning, Monitoring	daily	Warnings, EW	Discuss impact, mitigation
	Quantity Surveyor	Planning, Monitoring	daily	Warnings, EW, CE	Discuss impact, mitigation. Elevate warning
	Sub-contractors	Warnings, Compensation	If active on site	Warnings, EW, CE	Discuss impact, mitigation. Impact evidence
Management	Commercial Team	Warnings, Compensation	Weekly	EW, CE	Impacts, mitigation for Risk meeting & Evidence collection for CE
	Contract Manager	Warnings, Compensation	Weekly	EW, CE	Impacts, mitigation for Risk meeting & Evidence collection for CE
	PM (client)	Warnings, Compensation	Weekly	EW, CE	Signing off CE
	Agent/PM (contractor)	Warnings, Compensation	Weekly	EW, CE	Impacts, mitigation for Risk meeting & Evidence collection for CE
HQ	Corporate Risk	Project data review, Claims	Bid / Review / If claims made	CE	Analysis
	Legal	Escalated events	If event escalated	CE	Arbitration
	Insurance	Claims, Adjustments	If claims made	CE	Parametric payout

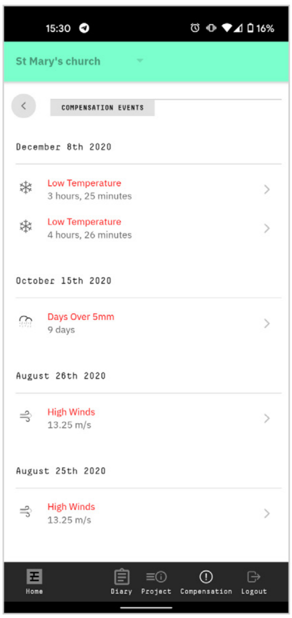
Notifications Key	
Warnings	Any weather event that could impact project
Early Warnings	Any event which could impact project and is officially registered
Compensation Events	Any event which passes the test (impact of that event also added if relevant)

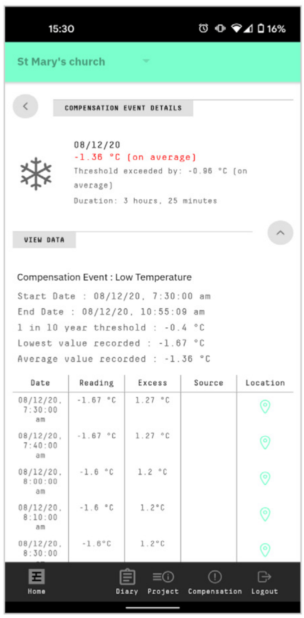
Appendix C: Questionnaire for experience sampling

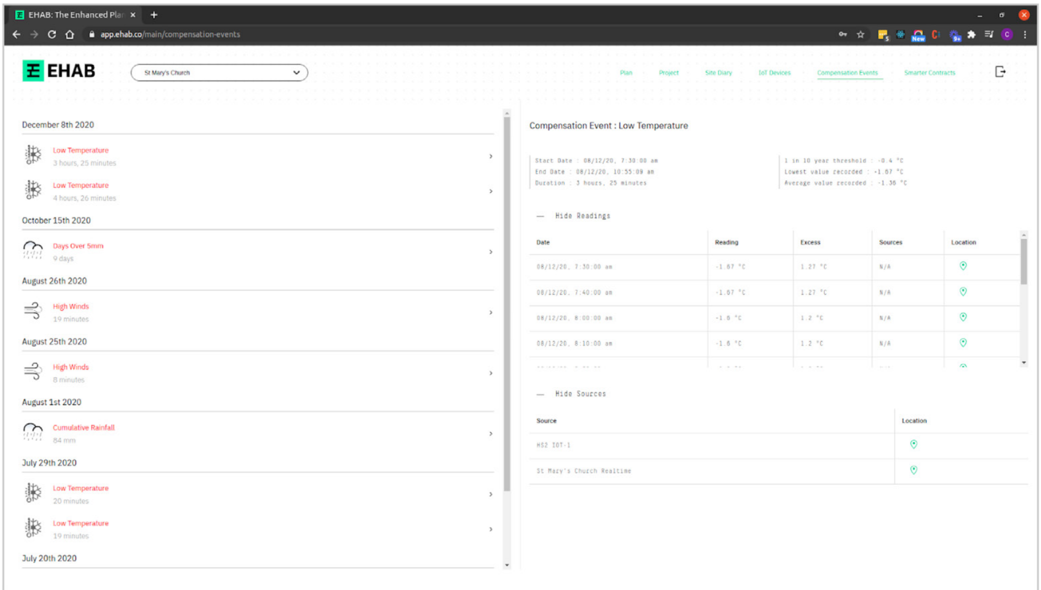
1. Do you think the site has experienced weather that could become a compensation event this month (for example one-in-10 year weather event or as per your contract)?
2. How much time did it take to check if the weather event was one-in-10 year event?
3. Was the event positively identified as one-in-10 year event?
4. Was a compensation claim raised?
5. How much time did it take to raise the compensation claim?
6. Were there any adverse weather conditions today?
7. How much time did it take to check and record the weather conditions?
8. How much time did it take to assess impact to current project plans?
9. Select the type of weather condition that affected your work today
10. Were there any actions taken to mitigate the effect of adverse weather?
11. What mitigation action was applied to get the project on track?
12. How much time did it take to carry out the mitigation action?
13. If there had been no mitigation/ rescheduling, what costs would have occurred?
14. What impacts and costs still occurred anyway due to the adverse weather?
15. Did the EHAB app assist you in your mitigation decision/ response? If so, how?
16. Were there any weather forecasts that triggered a decision/ action?
17. Which of these forecasted weather conditions triggered the decision/ action?
18. How much time did it take to study the impact of the forecasted weather condition?
19. Was there any decision or mitigation action that was applied to minimise the impact on the project?
20. How much time did it take to carry out the mitigation action?
21. If there had been no mitigation/ rescheduling, what costs would have occurred?
22. Did the EHAB app assist you in your forecast decision/ response? If so, how?

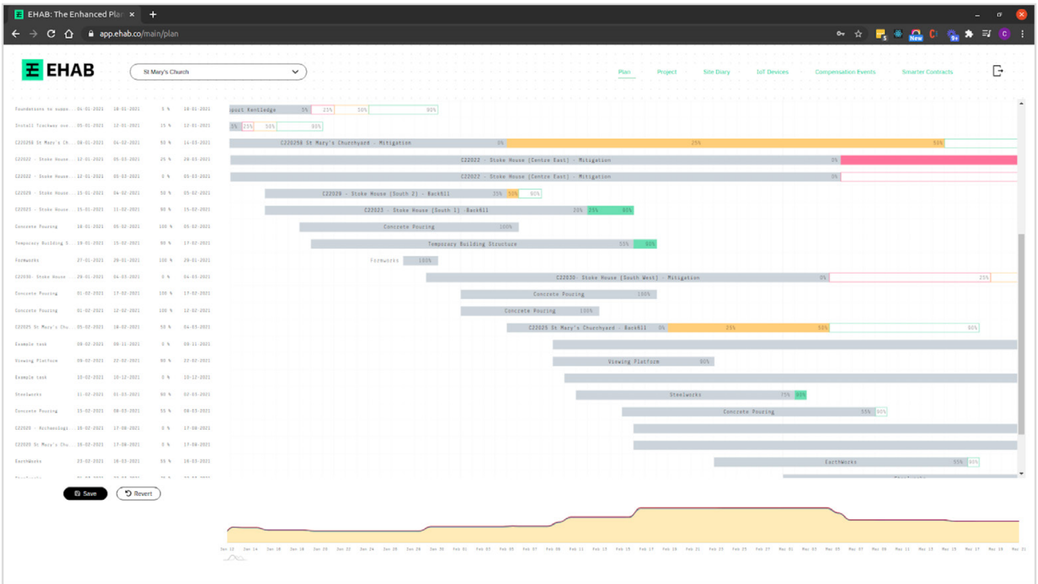
Appendix D: Screenshots of Weather Ledger Application








EHAB: The Enhanced Pla
app.ehab.co/main/compensation-events
EHAB
St Mary's Church
Plan
Project
Site Diary
IoT Devices
Compensation Events
Smarter Contracts
December 8th 2020
Low Temperature
3 hours, 25 minutes
Low Temperature
4 hours, 26 minutes
October 15th 2020
Days Over 5mm
9 days
August 26th 2020
High Winds
19 minutes
August 25th 2020
High Winds
8 minutes
August 1st 2020
Cumulative Rainfall
84 mm
July 29th 2020
Low Temperature
20 minutes
Low Temperature
19 minutes
July 20th 2020
Compensation Event : Low Temperature
Hide Readings
Date
Reading
Excess
Sources
Location
Hide Sources
Source
Location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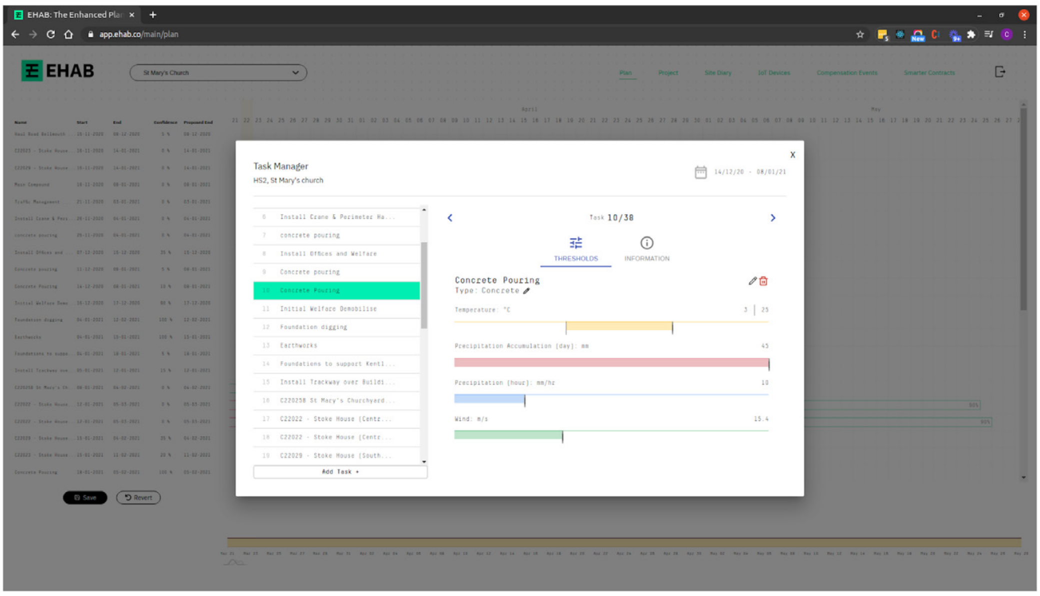
app.ehab.co/main/plan
EHAB
St Mary's Church
Save
Revert


EHAB: The Enhanced Pla
app.ehab.co/main/plan
EHAB
St Mary's Church
Task Manager
HS2, St Mary's church
Concrete Pouring
THRESHOLDS
INFORMATION
Add Task +
Save
Revert

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[4] Imagining construction's digital future. McKinsey & Company, Capital Projects and Infrastructure. June 2016.

[5] Construction's Digital Front Line. Autumn 2019. Retrieved from: https://www.causeway.com/hubfs/assets/documents/Front-Line-CDF19.pdf

[6] Guide to the effective deployment of IoT on construction sites. Weather Ledger project 2021.

Endnotes

1 Digital Catapult's technology exploration portfolio also includes: 5G, Artificial Intelligence and Machine Learning, and Immersive technologies (Virtual, Augmented and Mixed Reality).

2 Others identified by participants as future avenues for exploration include: improved payment automation, enhancing supply chain visibility, and reducing CAPEX by pooling heavy machinery between several companies.

3 The UK's innovation funding body, which operates with public money but at arms-length from the government.

4 https://www.decentlab.com/products/eleven-parameter-weather-station-for-lorawan

5 https://www.thethingsnetwork.org/

6 Oraclisation is the process of taking an event that occurs outside of a distributed ledger and wrapping in a deterministic (predictable and enforced) manner so that it can be loaded into and 'trusted' by participants to the ledger.

7 https://corda.network

8 https://www.openlaw.io

9 https://accordproject.org

10 https://docs.corda.net/docs/corda-os/4.6/key-concepts-contracts.html

11 https://chain.link/

12 https://provable.xyz/

13 https://tripetto.app/

14 https://www.wavewalkerbv.com/

15 https://www.w3.org/TR/vc-data-model/

Digital Catapult is the UK's leading advanced digital technology innovation centre, driving early adoption of technologies to make UK businesses more competitive and productive and grow the country's economy.

We connect large established companies, startup and scaleup businesses and researchers to discover new ways to solve big challenges in the manufacturing and creative industries. Through this collaboration businesses are supported to develop the right technologies to solve problems, increase productivity and open up new markets faster.

As well as breaking down barriers to technology adoption for startups and scaleups, our work de-risks innovation for large enterprises and uncovers new commercial applications in immersive, future networks, and artificial intelligence technologies.

Digital Catapult provides physical and digital facilities for experimentation and testing that would otherwise not be accessible for smaller companies.

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