

Article

Accelerating Use of Drones and Robotics in Post-Pandemic Project Supply Chain

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Abstract: The global COVID-19 pandemic forced the construction industry to a standstill. In the wake of the pandemic, this sector must be prepared to make bold, innovative moves to prepare for the future. Over the past few years, the use of drones and robotics has expanded with many commercial uses, including in the construction industry. Drone-driven automation has an enormous impact in improving productivity and reducing cost and schedule overruns. The use of drones, along with the application of Internet of Things (IoT) and robotics, can make a significant impact on the supply chain and improve inventory accuracy, leading to faster and more cost-effective building projects. This paper will propose and statistically substantiate an optimization model for supply chain management through the accelerated use of drones and Artificial Intelligence (AI) in the post-pandemic era. The use of smart devices and IoT will allow warehouse managers to have real-time visibility of the location and inventory tracking, as well as enabling warehouse workers to access information without being physically present. Cutting-edge drone technology can quickly perform inspections to make inventory control more economical and efficient. While they are certainly not a perfect fit for every building surveillance task, drones have many advantages for probing buildings in search of leaks, performing aerial surveys, and dealing with security issues more cost-effectively than manual procedures, thereby leading to improved communication and collaboration between different stakeholders. This paper includes a real-life case study and dynamic mathematical model to demonstrate how this approach results in a project's materials becoming visible, traceable, and easily tracked from end to end.

Keywords: drones; UAVs; IoT; pandemic; supply chain; projects



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1. Introduction

The global effect of the COVID-19 pandemic on the construction industry proved devastating, and the reverberations of its economic effect still keep many companies struggling to find new ways of managing capital expenditure projects with skeleton crews [1]. Numerous companies faced site shutdowns, worker layoffs, and diminishing funding. To address both short-term and long-term business challenges, the industry welcomed innovative breakthroughs to adapt to the post-pandemic construction environment [2].

The construction supply chain was shocked as a large number of projects were deferred and mothballed. The industry is still recovering from the supply chain crisis, including shortages of material and equipment. The focus on worker protection gave safety and inspection new meanings and a new direction. Travel restrictions increased the use of smart communication and added pressure to rethink the traditional construction approaches, with accentuation on accelerating the move to offsite construction methods. The number of engineers and specialty workers employed remotely increased tremendously. Although the ripples of the ongoing pandemic have subsided, the inflation and increase in cost of supply

chain continued, while the demand for faster and cheaper engineering and construction methods increased. To cope with a demand for more innovative construction methods and to stay competitive, vendors and suppliers need to optimize their time between working on site, in the office, and from a factory assembly. The supply chain's significant level of disruption and the ripple effect of material delays is likely to be felt for a significant period. There is an imminent need to manage projects using technologically advanced automation to facilitate managing projects in a holistic approach to enable a hybrid workforce.

Capital project execution strategies are changing from using a linear, traditional supply chain to a more unconventional new perspective. The supply chain already applies automation technology such as RFID, GPS, and Artificial Intelligence (AI). In the recent past, the use of drones and AI have been of tremendous help in improving construction safety, productivity, and cost, in addition to scheduling savings. Over the past few years, we have started to witness the use of drones on some construction projects on a limited basis, primarily as a means of documentation and data gathering. Drones have enormous potential in supply chain management as they reduce the need for human intervention on remote projects, or projects with high safety and security without exposing workers to risks. Furthermore, drones can access and reach isolated locations with pre-defined time and accuracy.

According to the latest McKinsey report, over the past three years alone there were over 660,000 commercial drone deliveries to customers, not including the countless test flights to develop and prove the technology with an estimated 2000 drone deliveries worldwide each day. The McKinsey report projected close to 1.5 million deliveries in 2022, or a 324% increase since 2018, as indicated in Figure 1 [3].

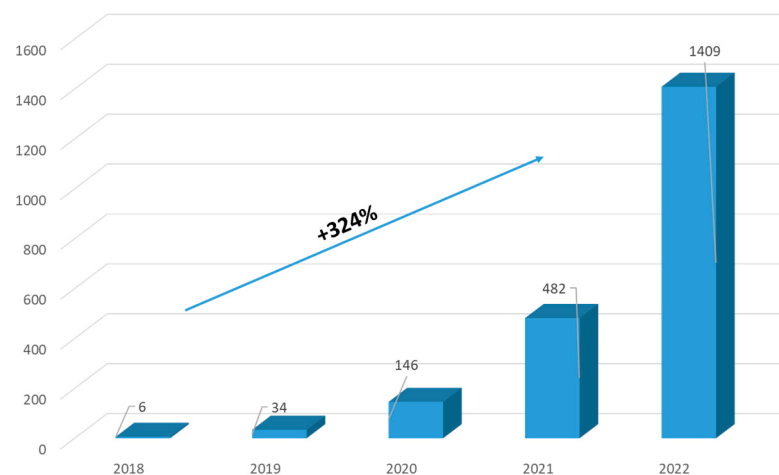


Figure 1. Number of drone deliveries (thousand). Source: McKinsey Drone Delivery Tracker & Forecast.

The pandemic helped accelerate the use of drones and obtained circumstantial relaxations over some of the restrictions on their use. Federal regulators issued new guidelines allowing drones to operate at night and over people, expanding their use [4]. In the recent past we have witnessed how drones helped the construction industry with topographical data, site photos, multimedia footage, expediting progress measurement, enhancing security, and facilitating inspections. The use of drones and the application of IoT can have a significant impact on inventory accuracy and other aspects of supply chain management.

This paper presents an optimization model for supply chain management through the accelerated use of drones and AI in the post-pandemic era. The paper starts with the use of drones in general, and supply management in particular. Although the topic of AI application to construction projects seems massive, the authors attempted to limit the study to the supply chain issues on construction sites and used even a narrower scope on the case study related to pipe spool prefabrication, which is a common problem in industrial construction projects.

The paper will demonstrate how this approach results in a project's materials being tracked from requisition to delivery and storage to meet or exceed the project's needs. Using the concepts of AI and the IoT, an optimization model is presented for project site warehouse management by using drones and robotics, along with the supported mathematical model. Drones equipped with video and GPS capability, and paired with smart tag readers, can monitor the status of materials in the warehouse, laydown areas, and fabrication shops [5]. This will enable the project team to monitor locations and quantities of assets instantly. The model presents a platform for the use of drones that instantly recognizes the location of required equipment or material, minimizing physical trips to vendor shops and fabrication yards. The use of this model would result in improved productivity and accelerated project execution time. The paper includes a case study focusing on pipe spool fabrication, which is at the heart of every industrial project.

The significance of this study is its contribution to improving efficiency with new ways of tracking jobsite inventory on capital projects. Drones, in conjunction with Radio-frequency Identification (RFID), QR-codes, and IoT, can be used to take physical inventory on construction sites, spontaneously locate site material in the construction warehouse, and quickly move the required material to the location where it is needed. This model saves thousands of hours over the construction duration by eliminating manual searches, thereby reducing the need for forklifts or other systems to transport boxes outside the warehouse for supply chain deliveries.

2. Literature Review

With the advancements in technology, automated vehicles have gained trending attention. In the supply chain field, they are being considered by retailers and courier services, and researchers are analyzing different methodologies to solve real-world problems effectively and efficiently. The authors of the study in [6] acknowledge that drones or UAV can operate autonomously by a preprogrammed flight plan. UAVs can perform delivery and pickup tasks faster than ground vehicles and often at lower costs, but they are limited by their battery life, distance reach, and volume or weight capacity. These characteristics have motivated probing for new vehicle routing solutions, and the whole stream of related literature is compiled in 79 articles and classified according to several criteria with a focus on logistics and optimization. A discussion then elaborates on directions for future research, including the use of drones in last-mile delivery and in humanitarian logistics.

The study in [7] argues that drones could be a viable option to improve the efficiency and effectiveness of supply chains working for humanitarian aid to combat the pandemic-originated supply crises. Specifically, the focus is on food, administrative, and healthcare supply chains, which are the core to combat the pandemic. The author in [8] considers the use of drones for the safety of workers at construction sites and safety improvements. The data were collected using a systematic literature review, semi-structured interviews, and a structured questionnaire. The surveys showed that drones are used for marketing purposes, followed by surveying application and quality inspections. Drones have proved effective in safety inspections, storm damage surveys, firefighting, waterproofing HAZOP areas inspection, etc., without putting workers at risk and in a cost-effective way. The use of drones is highly rated for working near the corner or edge of unprotected openings. Ironically, although the use of drones at times improves the safety of workers as it eliminates working in danger zones, one of the barriers to using drones involves safety concerns because they fly in the paths of cranes and heavy construction equipment, or over people in general.

The early warning system of the methodological framework considers machine learning, best utilization of resources, implementation of optimization, and simulation models. Through the advised framework, deep reinforcement learning is used to generate learning functions in reasonable computational times that satisfy constraints such as total number of deliveries and available time frame for operations, while it is also able to solve complex

problems that can reduce the cost of operations of the fleet, number of trucks utilized, and the utilization of resource capacity increased [9].

In construction projects such as bridge maintenance, road construction, and housing developments, the use of Unmanned Aerial Vehicles (UAV) has increased considerably. The research work in [10] utilizes techniques of deep learning and multi temporal images for effective identification of the changed areas and automatic detection of the construction site. With smart construction technology progress, the proposed methods will be helpful in construction management. The study in [11] presents a comprehensive review of applications of the Unmanned Aircraft System (UAS) in areas of civil engineering, such as infrastructure operation, construction, and environmental areas. It points out four future research directions and seven limitations by analyzing 2011 to 2019 publications with systematic reviews and meta-analysis (PRISMA method). In [12], the authors point to the limitation in safety monitoring systems and safe activities at construction worksites. This limitation is the absence of integration between the Internal Traffic Control Plans (ITCP). To overcome this limitation, the authors propose the use of deep learning, game engine-based ITCP and Unmanned Aircraft Systems (UAS) for safety monitoring. The study develops four rules to validate the presented concept of the ITCP-based digital safety monitoring system. The study in [13] discusses the use of drones in a relief distribution vehicle. It considers the maximum travel distance of drones without a need to recharge. This paper has proposed the best topology for both relief centers and recharge stations to cover a large-scale area with minimum and feasible incurred costs and waiting times. The resulting problem is solved using the genetic algorithm.

From this brief but concise review of the existing research, we presume the use of drones and aerial vehicles is worth investigating in different industrial areas, such as logistical systems, health care systems, disaster management, inventory management, spraying fields, performing surveillance in precision agriculture, environmental monitoring, construction site inspection, and last mile delivery. Integration of aerial vehicles with well-known NP hard problems such as Travelling Salesperson (TSP) and Vehicle Routing Problem (VRP) is a rather new research area. However, a large research gap exists due to limitations of safety and control issues. To the best of the authors' knowledge, drone-based warehouse management and quantity surveillance integrated with state-of-the-art technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) needs to be explored.

3. Post Pandemic Construction Era

The global implications of the pandemic transformed everyone's lifestyle and the environment they worked in. The change was significant, swift, and lasting in most cases. Within the first couple of months, it shocked the supply chain. A recent McKinsey poll shows how the overall impact was felt worldwide, expecting slow growth and a muted recovery. Freeing up cash by deferring or cancelling capital expenditures was one of the fastest ways to mitigate the economic effects of the pandemic in the short term. The challenge was how deep to cut and which projects to defer or cancel. The industry was faced with layoffs, as experienced by 40% of construction firms [14]. While companies were challenged to make quick changes to survive the fallout in the short term, there were certain implications for how they should use innovative ways to prepare in the long term. This included adopting new safety procedures for handling materials as well as transferring tools and equipment between jobsites, prioritizing projects, and adopting smart technologies and adapting them with new tools and approaches to support the ailing inventory management.

However, the construction industry, in general, has been reluctant to try new innovative approaches unless it is dictated by the client or can give the contractors a competitive edge. We are witnessing more clients insisting on using innovative approaches, including modernization and the use of Artificial Intelligence (AI). These should encourage them to expand the use of AI and drone applications to construction projects.

Many companies reorganized their supply chains and set up remote operations. A fast return to business-as-usual seemed unlikely [15]. Over the next five years, we will see higher construction costs, longer project schedules, and massive changes to the supply chain vendors that provide construction materials and equipment. We must prepare for what the construction industry will look like post pandemic. As projects get back to a new norm and most of the cancelled or deferred projects are reinstated, some experts predict a new construction boom [16]. Projects will face new challenges with increased personnel working semi-remotely, supply chain commotions, social distancing and other safety regulations, and increased restrictions on project budgets. Together, these present a challenge for organizations to rapidly change their processes. It is expected that the industry will have a heavier reliance on technology, remote systems, and automation, with high stress on prefabrication and substantial modularization to reduce the overall project duration.

There is a penetrating need for the use of high technology in the supply chain. This will be challenging, given the fact that the construction industry has historically been slow to adopt technology, [14]. There is a parallel in the recovery steps companies took after the 2008 financial crisis. In general, companies that came out ahead after this economic downturn typically moved fast and hard on productivity (including cost reduction), rapidly reallocated resources, and made bold moves to prepare for the future. Companies invested heavily in digital technologies, diversified their portfolios, and cleaned up their balance sheets [15].

Nevertheless, within the next five years we will witness an increase in technological innovations being used across the industry. The increased use of prefabrication and modularization still has not been widely adopted by the industry. The Contractors Association of America reported that 23% of firms had taken steps to implement tools such as offsite prefabrication to improve jobsite performance. However, modular construction is expected to increase, with an annual growth rate of 6.5% by 2026 [14]. What is more, approximately 90% of firms using prefabrication reported enhanced productivity, improved quality, and increased schedules when compared to traditional stick-built construction. Soon, capital projects will see more Augmented Reality (AR), Virtual Reality (VR), Building Information Modeling (BIM), robotics, cloud software, modular construction, and more. The industry, which was already suffering from a skilled labor shortages, will see new technical solutions to reduce the demand for physical labor. Project automation serves a vital role in mitigating the challenges that Engineering-Procurement-Construction (EPC) companies face. There will be an increased emphasis on tools that facilitate more remotely executed and monitored projects, including the use of robotics. There will be heavy emphasis on safety, with restrictions on the number of personnel working together in the same location and a reduced or staggered workforce, and it will also allow extended deadlines compared with traditional methods, if possible. Many of the service functions, such as architecture, engineering, and project management, will be carried out remotely or at least in a hybrid environment. Production of some of the construction components will be shifted to offsite locations. Construction companies will embrace the innovative technologies for project monitoring and management, which will lessen the need for being physically onsite. The application of drones and automation on capital projects promotes social distancing, safety, and high productivity. The extensive use of modular design and construction, as well as the use of drones and robotics, will help meet such challenges. Drones facilitate data being available in real-time to help resolve contractor, subcontractor, vendor, and client disputes. They can effectively document delays using real site data at the time of demobilization when the project handles potential issues that could arise during the construction process. Other factors, such as labor shortages or changes in project requirements, definitely impact the success of a construction project, and the increased use of automation and modularization will help in minimizing these issues.

During the past couple of years, engineers, architects, technologists, and project management personnel were given the option to work remotely. What surprised everyone

was the increased productivity from working remotely. Workers proved that not only could they work remotely, but the work could be carried out even more efficiently with greater enthusiasm, hinting towards a sustained hybrid work environment by combining remote and in-person work to establish it as a new norm. This trend is expected to continue in the future, and we will see very exciting developments happening in the coming years [17].

4. Use of Drones in Managing Capital Projects

A “Capital Project” improves a capital asset when the performance, value, or capability of that asset is significantly increased, or its useful or economic life is extended by more than one year [18]. The City of Portland defines Capital Projects as “a project that helps maintain or improve an asset, often called infrastructure... It is a new construction, expansion, renovation, or replacement project for an existing facility or facilities. The project must have a total cost of at least USD 10,000 over the life of the project ... OR a purchase of major equipment (assets) costing USD 50,000 or more with a useful life of at least 10 years ... OR a major maintenance or rehabilitation project for existing facilities with a cost of USD 10,000 or more and an economic life of at least 10 years” [19]. In Oil and Gas projects, the minimum threshold for capital projects is usually set at a much higher value.

Capital projects usually employ large numbers of engineers, vendors, contractors, and subcontractors, with the capital project stakeholders frequently located in multiple locations. They typically include pieces of equipment with long lead delivery times of months or years. This complexity, along with other factors, puts capital projects at a high risk of increased cost and schedule overruns. A survey by Ernst & Young shows that approximately two thirds of major capital projects suffered both cost and schedule overruns [20]. Delay in materials and equipment is a leading factor for slippage in capital projects, with the most influential cause of delay in material supply found to be poor material procurement and inventory management [21]. With more and more construction material and equipment being prefabricated and assembled off-site, the critical path or drivers of schedules will shift offsite rather than to the construction site.

The emergence of Building Information Modeling (BIM) is influencing design and construction processes and how project teams collaborate. BIM encourages the construction supply chain to use offsite construction using modularization. Modularization involves producing standardized components of a structure in an off-site factory, then rapidly assembling them on-site. Shifting construction away from traditional sites and into factories is changing the way we execute capital projects. Modular construction and BIM are recognized as important technologies. Modular construction is an off-site construction method that can eliminate time, cost, and material inefficiency by performing numerous construction processes via prefabrication at the factory. An example of modularization gaining popularity in capital projects is skid-mounted equipment, where the process equipment is contained within a frame and mounted on a skid. As a result, transporting and storing the machinery is safe and convenient. Another example is pipe-rack modules fabricated off-site, offering a terrific opportunity for schedule savings. The factory-controlled process allows resources to be optimized, generating less waste, and reducing site disturbances. Because the modules can be manufactured in parallel with site work and their manufacturing is not hindered by other logistics delays, projects can be completed faster than with traditional construction methods.

Drones and UAVs can help expedite modular and prefabrication processes and accelerate construction schedules. McKinsey reports that UAVs dramatically improve project accuracy and speed of completion [22]. Using robotic technology, work is carried out quicker and more cheaply, and with enhanced precision. With the greater development in robotics machinery, one can expect traditional construction activities such as welding, material handling, packing, dispensing, and cutting to be fully automated. This will not only allow for precision and accuracy throughout all construction processes, but also represents significant time and financial savings in projects [23].

According to an article on the expansive role of drones, namely, ‘Breakthrough Technology For The Civil Engineering Industry’ by the Carroll Engineering Corporation, “drones are becoming more and more common in many sectors of the economy as they guarantee the fastest and most accurate collection of detailed data. This technology, which is developing at a very fast pace, means that drones have been used for increasingly complex tasks. They have become a crucial tool for the efficient work that survey technicians and engineers conduct”. The article elaborates in detail on how drones effectively support their projects in the matter of:

- Site Reconnaissance
- Roadway Assessment
- Culvert/Bridge Inspections
- Streambank/Steep Slope Access
- Park and Open Space Aerial Imagery
- Water Tank/Standpipe Inspection
- Building/Roof Inspection
- Treatment Plants
- Orthophotography
- Terrain Modeling
- 3D Mapping
- Construction Inspection

Large commercial construction projects have started using drones, from real-time site monitoring to maintaining safe social distancing. Because travel restrictions and social distancing prevent many normal in-person site visits, drones are providing high-resolution images of jobsites, all while maintaining safe distances. A considerable number of contractors have already utilized drones on their construction projects. Turner Construction Company is a pioneer in this area, with a pilot program during the construction of Golden 1 Center for the Sacramento Kings. The project was a partnership between a University of Illinois research team and Turner and began in January 2015 [4]. The project utilized next-generation technology, with both images and videos captured by camera-equipped drones and four-dimensional BIM. This pilot study used elements of construction in the project schedule grouped by their location in 3D, streamlining the management of weekly work plans. The project management team can then mitigate potential schedule risks before they happen as the drone can observe the site from above, track things down, and enable real-time checks against the project schedule. To sum up, Drones helped the team to highlight issues with the project schedule, reveal worker productivity levels, identify areas of waste, and make scheduling improvements.

Chasco Constructors, a General Contractor and Construction Management firm, used drones to monitor the progress of the work, supervise subcontractors, and track materials and equipment. “Construction crews working on a 50-acre site in Texas did not even notice that one of the project’s most valuable assets was hovering just a few hundred feet overhead. Flying a drone over the site gave project managers unprecedented insight into the project and helped them achieve massive ROI” asserts Michael Lambert, Virtual Design and Construction Manager at Chasco [22].

Bechtel, one of the largest EPC companies, was among the first construction companies to be granted permission for the commercial use of unmanned aerial system technology by the Federal Aviation Administration (FAA). DPR, Layton, McCarthy, PLC, and other companies are among the first major construction companies in the US to use UAVs on their projects. “Denver-based PCL Construction has utilized drones for more than three years on nearly all of its major projects to improve jobsite communication, perform volumetric analysis, overlay design documents with installed work for visual verification, verify grades and provide historical documentation” [23].

4.1. Drone Use throughout Capital Project Lifecycle

Every stage of a capital project can benefit from using drones. Figure 2 shows the use of drones throughout the capital project lifecycles, from feasibility and bidding to handover, operation, and maintenance [22].



Figure 2. The role of drones throughout a project life cycle.

During the feasibility and front-end engineering design stages, drones help produce the data used to create 3D models of the existing conditions. A drone can capture views from any height and in any direction and produce high-resolution photos for a superbly detailed site plan.

Drones' ability to easily capture site information expedites detailed design preparation. Using new photo-mapping software, more accurate 3D models of the existing site and adjacent buildings can be created. This can be used to extract contour maps and site plans and may be imported into design modeling as a base for renderings, 3D printing, site layout, and providing 3D scans of existing structures, thus creating dynamic virtual building models.

The largest area where drones can provide cost and schedule improvement is in material procurement. Drones can help with inventory management and material requisitions from end-to-end in the procurement cycle. They can check stockpiles of materials and determine their quantity in just minutes, resulting in significant savings in time and labor costs.

As construction begins, drones help capture progress with aerial photos, eliminating the need for more expensive and time-consuming aircraft photography, which also has a high carbon footprint. Drones can capture videos from any height, angle, and in much greater detail in a few minutes.

Drones can facilitate project handover and highlight various features of the project. Aerial photos of the site can explain how the design fits within the larger context. They also provide an audit trail of project data and as-built information that helps facilitate final handover and adds value in operation and maintenance.

Until recently, the lack of FAA rules and regulations was one of the challenges facing drone use. In January 2021, the FAA granted Massachusetts-based American Robotics permission to operate automated drones. The FAA permission is a milestone, making it the first drone technology to be able to operate continuously without the cost of having a human operator on site. Although the decision limits operations to areas with light air traffic and daylight operations, the permit requires the drone not to exceed an altitude of 400 feet [24]. This permission will lead to minimal environmental impact as it involves small aircraft carrying no crew, without even an operator on the ground. To further minimize the hazards of flying drones when people are working, drones can only fly once everyone

has left work for the day and on the weekends. Nevertheless, the authors found very little research in terms of the application of drones to organize construction material, track prefabrication activities, and deliver the needed equipment and material to the end user at the jobsite.

4.2. Drones and Robotics in Supply Chain Management

Innovation is the key to managing the supply chain following an economic downturn. “This can only come about from digitalization, which will give organizations the effectiveness, transparency, and resilience they need” [25]. We need to create a supply chain environment so that companies will have precise, real-time visibility from identification of the needed material to creation of requisitions, purchase orders, fabrication, and transportation and site storage of the material.

Construction material and equipment both have a direct impact on a project’s performance as they account for 50–60% of the total cost of a construction project [26]. Their impact on a project’s timeline is also significant in terms of delays in material delivery, material handling, and identifying wrong or defective material. Traditional mitigation steps such as expediting the material using air shipment, paying premiums to advance orders, etc., are not as effective because they provide only a partial solution with additional risks of claims and litigation. Stockpiling plenty of inventory to prevent delays poses its own variability and may even prolong the execution time. Having too much inventory leads to other issues, such as loss, spoilage, expiration of warranties, etc., all of which can lead to re-work, re-order, cost overruns, and longer cycle time.

Capital projects are complex and generate enormous amounts of documents, most of which are not retained or archived for future reference or use. The commercial use of drones has been deftly enhanced and automated. Drones are now increasingly dependable, affordable, fully autonomous, and highly accurate in image recognition. Their induction, combined with IoT, minimizes the use of bar-codes and RFID scanners for inventory management, leading to improved inventory accuracy. Using IoT technology, drones can both gather and receive information. An IoT system consists of sensors and devices that communicate to the cloud data storage through connectivity software that gives instructions to perform an action. A sensor provides feedback on a process or element in a measurable manner. IoT technology provides drones with the capability to perform operations from any device connected to the internet. IoT technologies and AI can power the drones, augmented with RFID, sensors, and robots, to perform real-time analysis, providing the intelligence in site warehouse automation to fly autonomously while carrying payloads, avoiding obstacles, and navigating indoors with accuracy.

The application of IoT is enabling drones equipped with RFID readers to replace barcodes, which used to be the standard method for tracking the manufacturing and delivery of products in real time. The data captured by these drones will help companies better manage quality control, on-time deliveries, and product forecasting. Drones can fly autonomously using advanced sensors, which can facilitate managing a project’s Warehouse Management System (WMS). Drone-powered software creates an optimal path for the drone to travel based on mapping performed previously without using markers or lasers to guide it through the warehouse. When it passes through the warehouse directed by the X, Y, and Z coordinates, it can quickly scan labels and take the required action to fetch the material or simply count inventory.

Drones can also be used to capture valuable information on the status and productivity of construction equipment. They can provide status updates on the working state of equipment. Drones save substantial time when used for equipment inspection, especially in remote areas where equipment is difficult to access. For example, a drone conducted an “almost four-mile linear inspection of the Trans-Alaska pipeline” without needing a ground observer, and the team involved in keeping the drone flying was able to conduct the inspection off-site [27]. The IoT technology and smart sensors can tag activities and transmit these to other smart devices or computers. A smart sensor can include technologies such

as microprocessors and connectivity to obtain feedback signals. There are diverse types of smart sensors, such as heat sensors, sound sensors, smoke sensors, light sensors, and fire sensor, that collect and analyze data from various sources and provide equipment status and productivity. The use of smart sensors permits warehouse workers to have real-time visibility of the location and progress of inventory. Wearable smart devices free up warehouse workers to move anywhere in the warehouse and enable them to access information without being physically present. A drone can read barcodes on pallets using attached scanners, taking inventory of a location in 6 s, and sending the information to the computer [28]. The drone performs this task autonomously, saving countless hours.

5. Proposed Original Method

In this paper, we propose a conceptual model, referred to as the Drone-Based Capital Project Optimization Model (DBCPOM), which can be applied to manage the supply chain on a capital project jobsite warehouse. The DBCPOM model is unique as it integrates AI technology with IoT and RFID sensors, allowing drones to scan the sensors and use an IoT platform to keep track of physical material supply, as well as fetching the required inventory in real time. The DBCPOM has its own system architecture that is original, consisting of a three-phase system architecture, which is explained in detail under the “Three-Phased System Architecture” section in this paper. The concept is augmented with a simulation platform consisting of mathematical prototypes and assumptions.

Figure 3 is a general graphical representation of the proposed model on the use of drones in a jobsite warehouse.

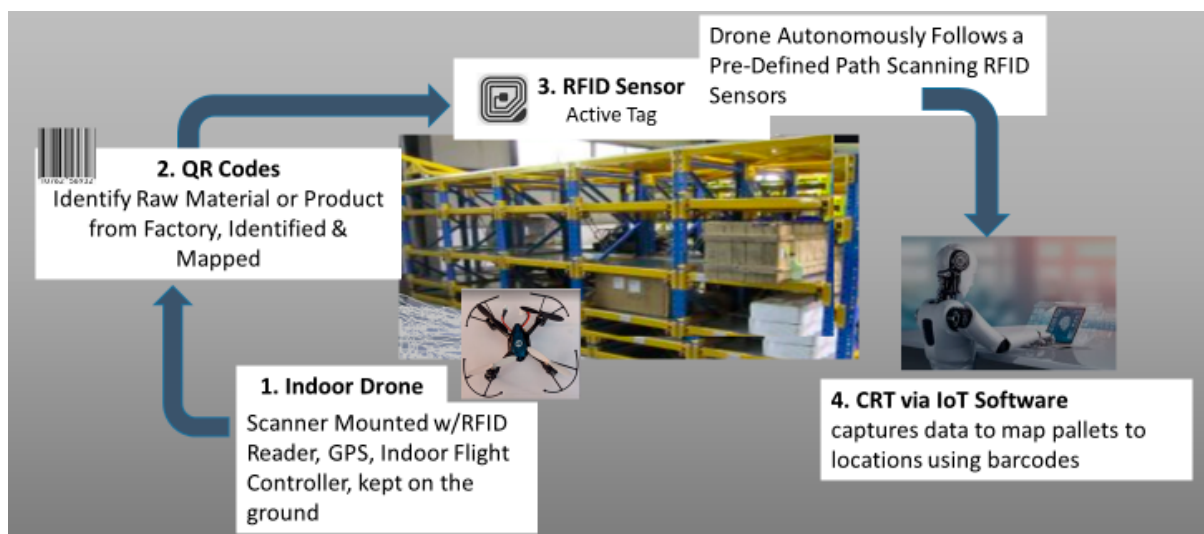


Figure 3. Drone-based capital project optimization model (DBCPOM).

The scanner-mounted “indoor” drone with RFID reader is enhanced with barcodes or Quick Response (QR) codes, which can store more data than normal barcodes. The latter can identify raw material or products from the factory and map the results. However, QR codes require a dust-free environment, which is hard to find at construction sites. The use of RFID to identify objects is a turning point in inventory control, as RFID uses radio waves to communicate between a tag on the product and the reader. When a shipment arrives, an RFID tag can be attached, and smart sensors are used to identify the objects on the rack using an electromagnetic signal to transmit the information to a central database where they are analyzed—by warehouse management software.

RFID sensors are “active,” with their own power source to send and receive data. The RFID sensors do not need batteries as these are powered by the radio frequency energy transmitted from RFID antennas. RFID sensors use an IoT platform to keep track of physical material supply and allow users to track inventory in real time. IoT is the engine behind

inventory management, facilitating connected devices across all technologies. It helps extract Required On-Site (ROS) dates from the schedule and communicate with RFID tags and sensors.

A “key” difference between the proposed method versus other methods is that the proposed model-based system utilizes the integration of AI, IoT, and RFID sensors transmitting data to a central database that is constantly communicating with “smart” drones that can scan, receive, and transmit data at the jobsite. Other systems and methods consisting of mostly segregated parts are not integrated, and most importantly are not tailored to be used on capital project jobsite supply management.

The proposed original model is illustrated by applying it in a case study. According to the proposed model, this is both possible and expedient with this conceptualization in mind. Let us now turn to a case study to illustrate how the model can be applied in practice. We have used a pipe spool fabrication shop as a case study to help illustrate how our proposed drone-based model can be applied as a viable experiment to evaluate the results of the proposed methodology.

6. Case Study: Pipe Spool Fabrication

To help illustrate the proposed drone-based model, a typical pipe spool fabrication activity for an oil and gas megaproject is examined as a case study. Installation of large pipe spools is normally an integral part of any process plant construction. Most industrial projects have complex process piping that requires engineering, procurement of raw material, and then shop fabrication to fit it before it is installed and tested in the field. The pipe spool fabrication shops are usually located either inside or in the vicinity of the industrial projects. The associated ‘cut and weld’ activities are always critical, contributing to major delays or rework. Pipe installation accounts for 45% of the cost of plant construction [29]. The prefabricated components of a piping system are called spools, and they include the pipes, flanges, and fittings, and are assembled in a fabrication shop near the project site. Normally, designers show the location of field welds on isometric drawings, but the pipe manufacturing contractor makes pipe spool drawings based on the field welds. A process plant comprises hundreds of steps involving thousands of pipe spools connected and welded to fittings, flanges, gaskets, and fasteners, cut into required lengths and pre-assembled at the fabrication shop near the jobsite. The spools must be fabricated in the required installation sequence and delivered in time to avoid slippage. These are recognized as critical processes, and contractors require a substantial backlog of fabricated spools before they can start actual piping installations.

The flowchart in Figure 4 shows the current pipe spool process from engineering to procurement, shop fabrication, and finally field installation. Pipe spool installation is a complex process that starts early during the engineering design, with the Piping and Instrumentation Diagrams (P&IDs) showing the piping and process equipment together with the instrumentation and control devices. The P&ID and a 3D model is required to produce piping isometrics. The 3D model shows optimized piping runs, and along with the P&ID provides the quantities and types of material to identify preliminary Material Take Off (MTO) to prepare piping requisitions and issuance of piping purchase orders to obtain the required raw material. The P&ID and 3D model are also required to prepare the piping isometric drawings, which show details of each pipe spool ready for manufacture and assembly. Before pipe spool fabrication can start, decisions must be made as to the location of the fabrication shop, the actual construction of the shop, and acquiring the required resources such as pipefitters and welders. It is also a mandate to have the required welding procedures and to inspect the shop to assure that sufficient resources, such as certified welders, are available to start spool production. In addition, the contractor prepares spool shop drawings using the isometric drawings. The fabrication shop uses spool isometrics to build the pipe runs. The spool shop drawings show everything that is welded together in one single drawing, broken by pipe runs at flanges and identified field welds. Once all this is ready, the fabrication shop begins to produce the spools.

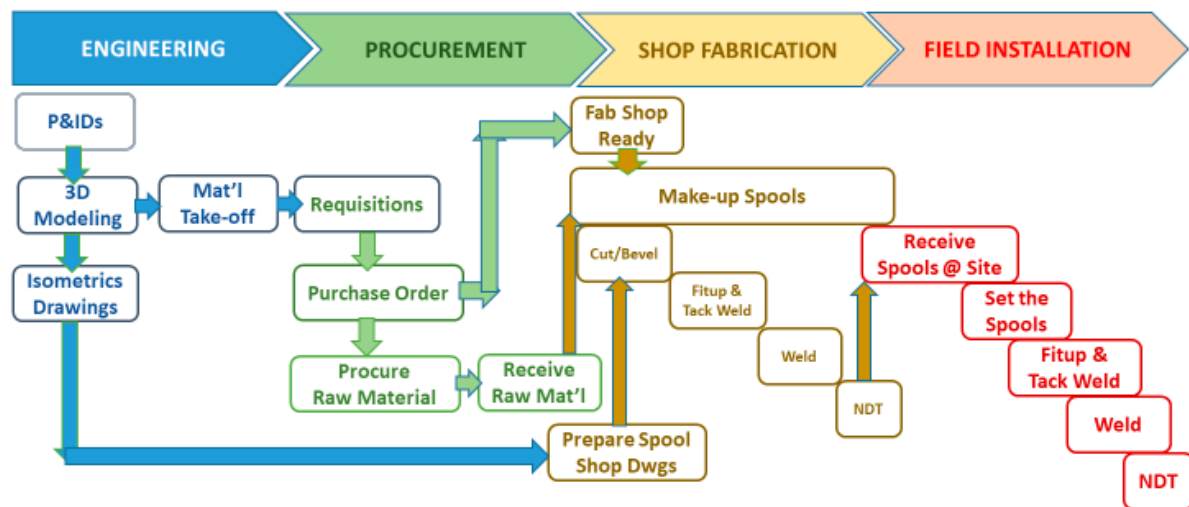


Figure 4. Current pipe spool pre-fabrication process.

The fabrication shop activities include cutting and beveling each spool, fit-up and tack weld, weld, and Non-Destructive Testing (NDT), to be sure that the fabricated spool is not defective. Once this is completed, the spool can be released to the field for installation. Once the spools are ready, they are usually stored somewhere as contractors may not be ready to install them. Field installation includes receiving the spools, setting them, fit-up and tack-weld, weld, and NDT.

The current pipe spool fabrication steps described above are mostly manual and subject to numerous errors and omissions. For example, the above process may result in materials on the P&ID drawings not matching the spools; mismatch in the dimensions of the spool and isometrics; missing spool pipes, elbows, or flanges; lost spools in the yard; or spool fabrication not according to the required installation sequence and priority. The process is indeed very linear, so if there is a delay anywhere during the process it will result in delay of the spool installation, and because they are on the critical path, it will impact the entire project completion. Furthermore, the isometric drawings are usually prepared early in the model review. Any revisions to 3D models or isometric drawings can impact the spool production. A study published in the Journal of Engineering Management shows that 20% of the spools in the fabrication shop experience material shortages and project schedule delays [30]. The process shortcomings are summarized in the following table (Table 1):

Table 1. Current process pipe spool shortcomings.

Project Stage	Process Shortcoming Problems
Engineering	- P&ID drawings not matching the spools. - Mismatch in dimensions of spool and isometrics
Procurement	- Material not matching the spools. - Delay in raw material pipe
Fabrication	- Missing or lost spool pipe, elbows, or flanges
Installation	- Spools lost in the yard

6.1. Proposed Improved Model for Pipe Spool Monitoring

Collaborative robots (Figure 5) can work with human welders to boost productivity. Novarc Technologies, a Canada-based robotics company, has already built and used robots specifically for pipe welding [31].

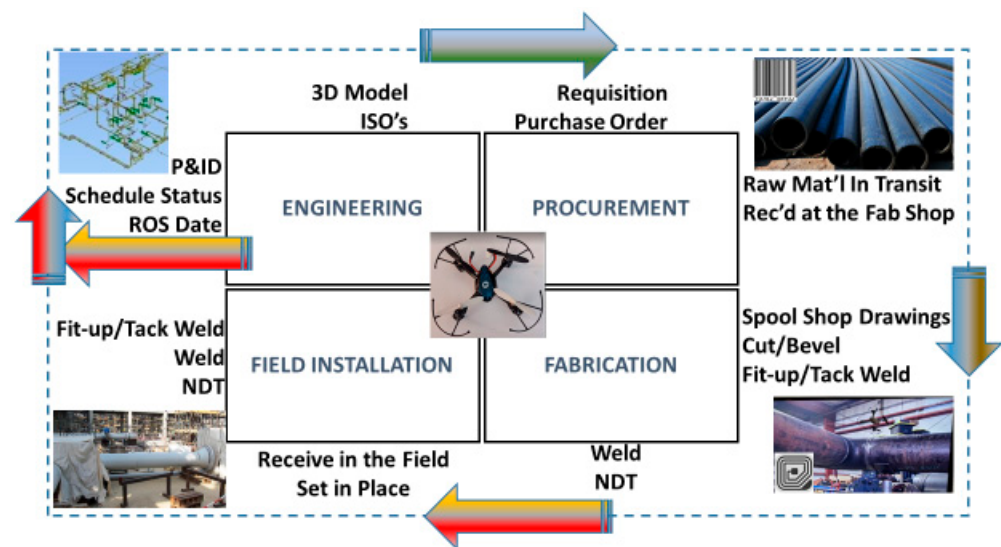


Figure 5. Improved process for pipe spool monitoring.

The proposed model in Figure 5 shows the improved process for pipe spool monitoring that starts in the engineering phase and continues throughout the procurement, fabrication, and field installation, with drones playing a vital role throughout this process. Drones can capture the status of P&IDs and schedule milestones when the raw material is required on site and follow the status of 3D model and material requisitions. As spool isometrics are prepared from the isometric drawings, the isometrics for each work area or work package are tagged with barcodes. Every welding detail is marked on the spool isometric drawings. The material requisition to procure the raw material is given a reference number, and as the PO is issued and the pipe is manufactured and shipped, each pipe or flange, etc., is given a barcode. The barcode shows pipe material, diameter, length, and plant location. The information regarding the MTO, Purchase Requisitions (PR), Purchase Order (PO), vendor status, and expediting actions are all pulled using RFID/IoT technology. This close monitoring continues end-to-end until the material is shown in transit or is received at the fabrication shop. The model is a two-way communication as it not only pulls and extracts data, but also provides information to update the 3D model and isometric drawings to pictorially show what spools have been fabricated, welded, or released to site. Drones can identify and update the spool fabrication process as they pass through the various gates.

6.2. Progress Status Using the Proposed Model

The schedule in Figure 6 was extracted from a primary critical path schedule using an actual project through the engineering, pre-fabrication, and pipe installation phases. Before piping prefabrication starts, fittings and gaskets (as reflected in the MTO) should have been delivered and piping isometrics issued so that piping spool drawings are prepared. The piping spool prefabrication duration at times takes several months, depending on the project. Contractors allow large buffers of pipe spools before starting field installation in order to have enough work fronts. In general, contractors do not start piping installation until they have over 50% of the spools prefabricated [32].

The master schedule is a CPM-based summary schedule using the “push” scheduling concept. In push-based supply chain scheduling, products are pushed based on forecast predictions versus in a “pull” system where procurement, production, and distribution are demand-driven. This schedule is usually not used to timeline every spool detail because that would be too much to plan in a summary schedule. However, the start and finish dates for every bar that shows groups of spool fabrication are used for integrated daily planning purposes. To have an integrated schedule, the project execution schedule must change from push to pull concept [33]. Under this concept, upstream activities do not start sooner than needed to assure the continuous release of downstream work. Spool

fabrication activities are more of a production process; therefore, the tools that are used in operations management can be applied. Using the primary schedule above, a phased schedule is produced by cross-functional management teams using the pull technique, working backward from a target completion date. Phased schedules feed into a look-ahead window, and the functional team will provide a buffer or schedule contingency to assure that project completion is not impacted.

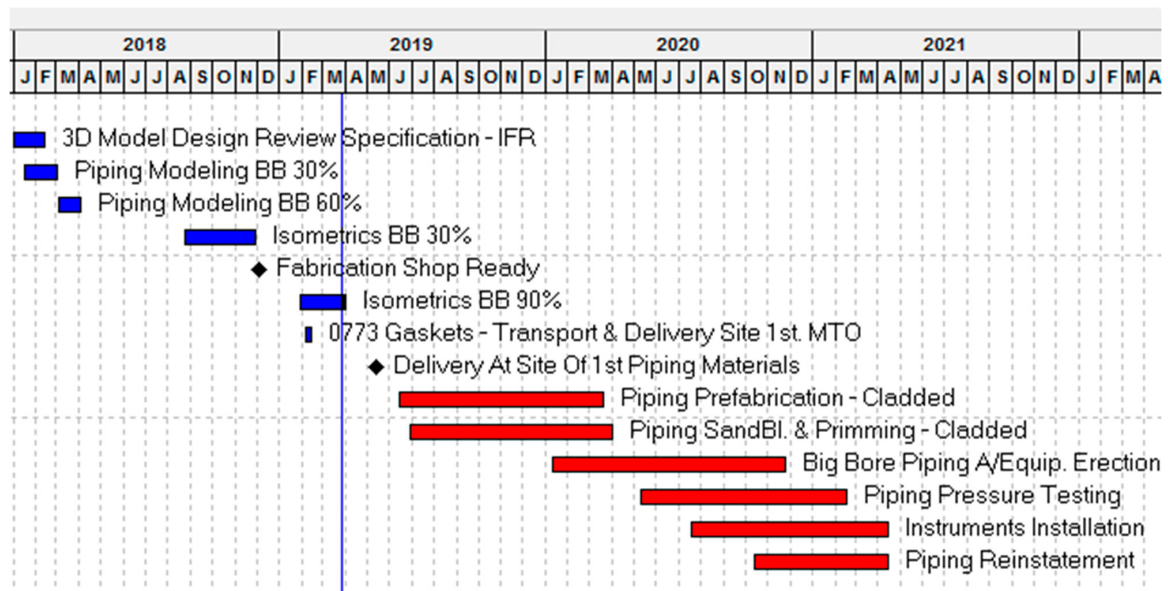


Figure 6. Critical path schedule through piping prefabrication and piping installation.

A typical process for pipe spool fabrication includes setup time, cut and bevel, fit-up and tack, welding, and Non-Destructive Testing (NDT). The performance of this process has a direct influence on field assembly and site construction, much the same as a manufacturing shop.

Spool fabrication planning is best done by the shop supervisor who controls the sequence and resources and is fully aware of material and resource availability. Planning follows a rolling two-week look-ahead schedule, as shown in Figure 7, which represents the fabrication of one spool. Usually, a fabrication shop is set up to process several spools simultaneously. This schedule shows the detailed plan to produce every spool that is required for each area or major equipment. The look-ahead window provides an overview of the activities that will take place in the next two weeks, which gives adequate time to ensure that everything is ready in terms of material and resources.

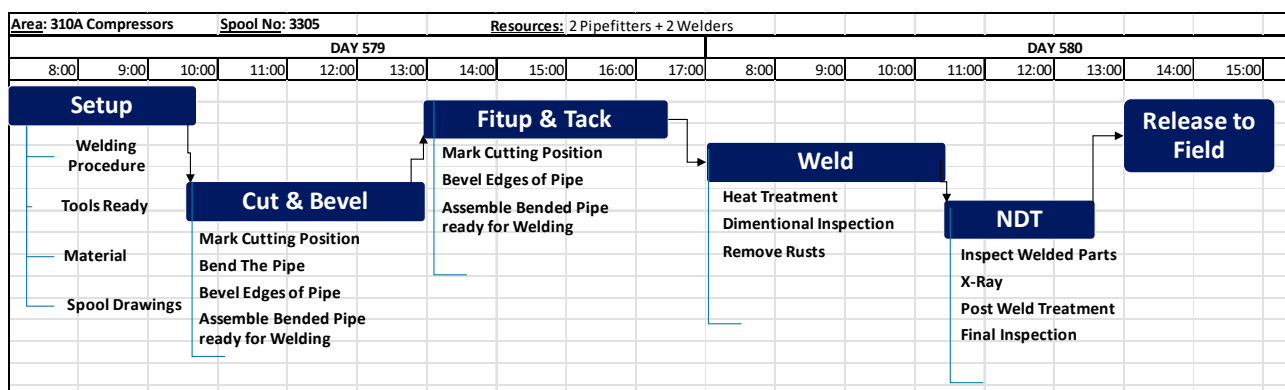


Figure 7. Daily production schedule for each spool (old method).

The drone, augmented by robots and IoT technology, facilitates progress at every step of the sequence, hence the progress of the spool fabrication is transparent at any point in time, as shown in Table 2.

Table 2. Pipe Spool Progress Measurement System.

Schedule Activity	Actual QTY by Drawing	Elementary Operations/Phases Breakdown						Item Progress	Earned Quantity			
P6 Activity XX330AP0017 Piping Pre-Fab > 2"		Transport to Shop	Cut & Bevel	Fit-up & Tack Weld	Welding	NDT/WHT/Release	Total					
DRAWING CODE		10%	20%	20%	40%	10%	100%					
		6173	86%	65%	60%	58%	58%			63%	63%	3877
		3980	80%	55%	49%	46%	46%			52%	52%	2066
	2058	75%	52%	38%	35%	35%	43%	43%	891			
	1473	33%	15%	10%	7%	7%	12%	12%	176			
S/T	13,684		20%	20%	40%	10%	51%	51%	7010			

The new improved method using the model is shown in Figure 8.

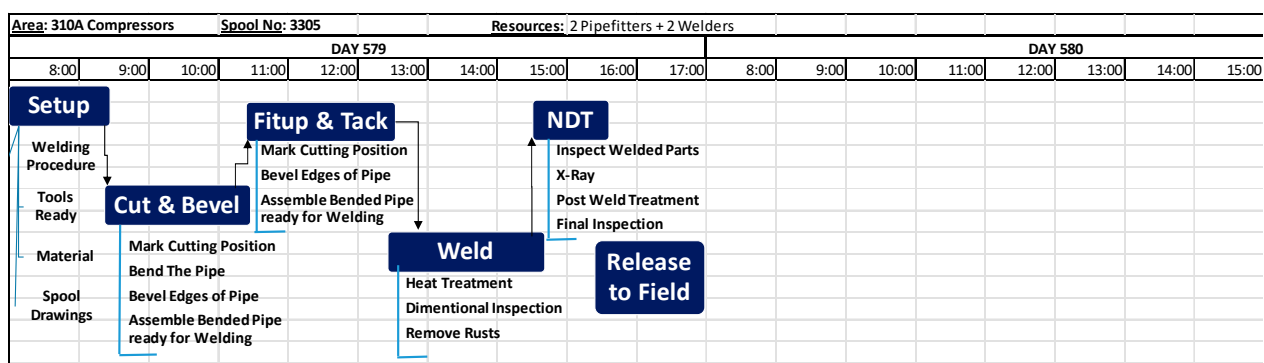


Figure 8. Daily production schedule for each spool (new method).

7. Performance Results of the Proposed Method

The case study reveals positive results using the proposed method, versus other methods. The results indicate a substantial increase in productivity and shop capacity, while demonstrating superior weld quality using the proposed capital project optimization model that combines robotics with AI and drone applications. The existing or “other” pipe spool fabrication methods are mostly manual and subject to errors. Furthermore, the existing methods often result in a mismatch of materials on the P&ID drawings, a mismatches in spool dimensions, or missing spools, causing delays in delivering critical material at the right time. Because most of these spools are critical for a capital project, its accumulation contributes to retarded progression of the project.

Comparison of the traditional method (Figure 7) and the new improved method (Figure 8) clearly shows that in only one pipe spool prefabrication involving a 20 h cycle, the cycle can be cut to only 10 h or a savings of 50%. A typical job prefabrication for pipe spools may take 6 to 8 months involving over 100,000 Diameter Inch (DI) of piping cut/weld that could take over 500,000 man-hours to complete. One can only imagine the

cost savings if this number is cut in half, as can be achieved by using this proposed new method.

Nevertheless, there have recently been a few research studies attempting to improve the process. For instance, Diogo Mendes Correia, Leonor Teixeira, and João Lourenço Marques presented a methodology on smart supply chain management during the 2021 IEEE 8th International Conference, which proposed an adapted framework from the quality management methodology to organize supply chains based on client's personalized inputs and stakeholders' integration [32]. Although the proposed methodology suggests improving supply chain management, it does not address the supply chain issues faced at any capital project jobsite. Furthermore, it is more focused on quality management and says nothing about the use of drones. On the other hand, Widodo Budiharto, Andry Chowanda, Alexander Agung Santoso Gunawan, Edy Irwansyah, and Jarot Sembodo Suroso presented a paper published by IEEE at the 2019 2nd World Symposium on Communication Engineering (WSCE), on the implementation of drones for agriculture, delivering items, and GIS [33], but their findings are not relevant to the supply chain issues.

Perhaps a more relevant paper was presented by Gabriela Ahmadi-Assalemi, Haider M. al-Khateeb, Gregory Epiphaniou, Jon Cosson, and Hamid Jahankhani at the 2019 IEEE 12th International Conference on Global Security, Safety and Sustainability (ICGS3), detailing a framework to facilitate the tracking of object behavior within Smart Controlled Business Environments (SCBE) to support resilience by enabling proactive insider threat detection. In summary, it focused on the integration of the Internet of Things (IoT) and Cyber-Physical Systems (CPS) into the supply chain to increase operational efficiency and quality. It introduced new complexities to the threat landscape [34]. However, the study was generic in nature and did not address the material supply issues at a capital project jobsite.

8. Three-Phased System Architecture

Material logistics requires that project supplies be delivered at the right time, to assigned locations, and in specified conditions. Managing end-user ordering time would be pivotal to the usage of drones (UAV)—a goal that can be realized by adoption of our three-phased approach illustrated below.

8.1. Pre-Order Phase (Phase 1)

In compliance with the materials management system, materials are tagged by RFID on arrival at the warehouse and subsequently stored in designated storage spaces. This is followed by data collection by UAV, which will transmit data to the Warehouse Management System (WMS). This will be verified by the WMS to ensure that materials are stored at the allocated locations, and if needed as a corrective measure, a WMS Remedy will be issued and assigned to the warehouse staff. Each WMS Remedy will generate a confirmation receipt for the project manager. The warehouse team will resolve the WMS Remedy and update the UAV, which in turn will validate the termination of this phase by confirming that the assigned task is accomplished. Finally, the project manager will receive a report for closure of the WMS Remedy.

8.2. In-Order Phase (Phase 2)

For any arrival of materials in the staging area, WMS will keep updating in real-time mode. UAV will perform quantitative assessment of the materials in terms of quantities, conditions, and specific locations, and will facilitate the immediate issue of WMS Remedy for any required corrective measures. To ensure optimum use and flow, materials should either be directly placed where they are needed or be kept provisionally in the staging area if not ready to be placed. Hence, WMS will send a notification if any material stays for more than five workdays in the staging area, which triggers the established escalation process and necessary implementation. In case storage in the staging area exceeds allocated limits, WMS will update UAV to issue a "capacity constricted" warning.

8.3. Post-Order Phase (Phase 3)

In this last phase, WMS will consistently receive updates from the UAV after the end-user completely withdraws materials from the staging area. The UAV will update WMS about material parameters such as quantity, conditions, and precise locations, which is passed on to the project manager. WMS will manage the returned as well as the stored materials based on predefined methods. Supported by the UAV-generated images of surplus material, a report would be posted on the company's corporate portal to initiate a product push so that excess material could be utilized in any ongoing or forthcoming projects.

Figure 9 shows the three-phased system architecture for the capital project model design.

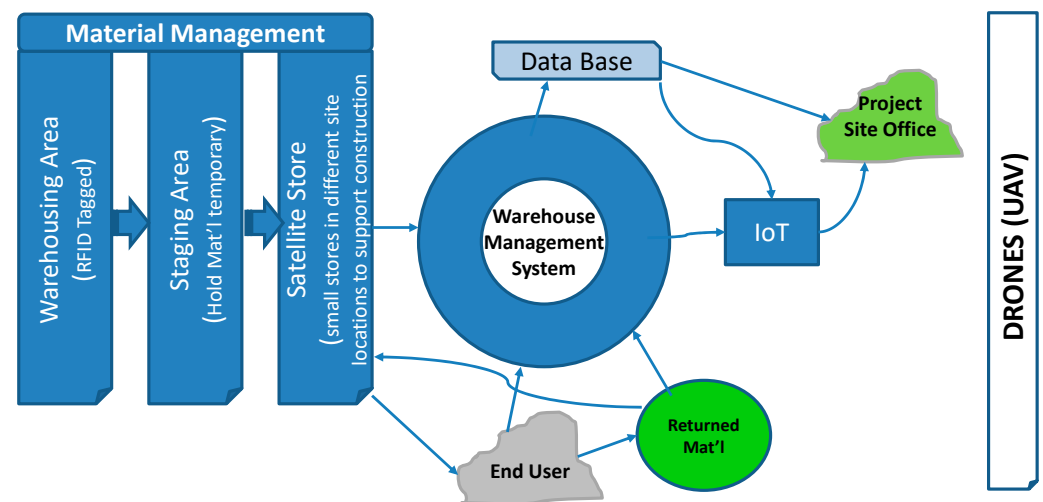


Figure 9. Three-phase system architecture.

From the scope of using drones in construction projects, it becomes evident that the following considerations are imperative while designing a new system architecture:

- The extent of autonomy and regulatory freedom for drone operations.
- The location of laydown areas.
- The type of material used in tagging and barcoding.
- The capacities of warehousing, storage, and inventory systems.
- Optimization of storage space by the using tall racks and aisles.
- The depth and arrangement of shelves.
- Storage space and orientation of cases, pallets, or cartons.
- The operational hours of warehouse and shops.

9. Mathematical Model

The below mathematical model is proposed to help the decision maker identify the optimal number of drones required to run their dynamic operations considering the overall cost and operational efficiency.

9.1. Model Assumptions

1. There are L types of equipment.
2. Equipment arriving at the warehouse is called inbound equipment, and equipment to be shipped to customers is called outbound equipment.
3. Inbound equipment arriving during hour t is assumed to be available for scanning at the beginning of the same hour. Outbound equipment scheduled for shipping during hour t is available for scanning at the beginning of the same hour.

4. The number of each type of equipment, whether inbound or outbound, is known and constant.
5. Scanning of equipment available at hour t is completed within this hour.
6. Scanning time for each type of equipment, whether inbound or outbound, is known and constant.
7. Drones assigned for scanning do not break down or run out of battery power.
8. A drone can operate continuously for a maximum of T hours.
9. A fresh drone with a full battery must enter service every m hours to act as a master drone.
10. A drone flies for a continuous period. It flies again the next day.
11. The drones' schedule repeats daily.
12. A cohort of drones is a set of drones that start scanning at the same time.

9.2. Model

We define the following parameters:

- $I_{l,t}$ is the number of inbound equipment of size l that are available at the beginning of hour t , where $l = 1, \dots, L$ and $t = 1, \dots, 24$.
- $O_{l,t}$ is the number of outbound equipment of size l that are available at the beginning of hour t , where $l = 1, \dots, L$ and $t = 1, \dots, 24$.
- TI_l is the time, in minutes, needed to scan one unit of inbound of equipment of size l , $l = 1, \dots, L$
- TO_l is the time, in minutes, needed to scan one unit of outbound of equipment of size l , $l = 1, \dots, L$

The total scanning time in hour t is given by:

$$S_t = \sum_{l=1}^L I_{l,t} \cdot TI_l + \sum_{l=1}^L O_{l,t} \cdot TO_l, \quad t = 1, \dots, 24$$

Hence, the number of drones required to complete the scanning in hour t is given by:

$$N(t) = \lceil S_t / 60 \rceil, \quad t = 1, \dots, 24$$

where $\lceil x \rceil$ stands for the smallest integer that is $\geq x$. To create the daily drone flying schedule, we introduce the following decision variables.

Let $x_{t,t+r}$ be the number of drones that will start service at time t and are still in service at hour $t+r$, $t = 1, \dots, 24$ and $r = 0, 1, \dots, T-1$.

The demand for drones in hour t is satisfied by drones that are active at time t , i.e.,

$$x_{t,t} + x_{\text{mod}(t-1,24),t} + x_{\text{mod}(t-2,24),t} + \dots + x_{\text{mod}(t-T,24),t} \geq N(t), \quad t = 1, \dots, 24 \quad (1)$$

A cohort of drones starts with $x_{t,t}$ members, some of which may retire before completing T service hours, hence we introduce the following constraints:

$$x_{t,t+r} \geq x_{t,t+r+1}, \quad t = 1, \dots, 24, \quad r = 0, \dots, T-1 \quad (2)$$

The cost of acquiring and maintaining drones is usually high, so the decision maker would be interested in determining the number of drones, D , that can service the daily scanning load. D is given by (3):

$$D = \sum_{t=1}^{24} x_{t,t} \quad (3)$$

The next costly item is the total flying hours; these are proportional to the operational costs. We use DF to denote the drone-hour, and it is given by (4):

$$DF = \sum_{t=1}^{24} \sum_{r=0}^{T-1} x_{t,t+r} \quad (4)$$

It should be noted that $DF \geq \sum_{t=1}^{24} N(t)$. If a drone is flying but not assigned a scanning task, then $DF > \sum_{t=1}^{24} N(t)$. In this paper, we find a drone flying schedule such that condition (4) is satisfied.

$$\sum_{t=1}^{24} \sum_{r=0}^{T-1} x_{t,t+r} = \sum_{t=1}^{24} N(t). \quad (5)$$

Finally, the decision maker would be interested in having a small number of cohorts to ease the planning process and limit the possibility of errors.

To be able to control the number of cohorts, we introduce a set of binary variables as follows:

$$y_t = \begin{cases} 1 & \text{if a cohort starts at time } t \\ 0 & \text{otherwise} \end{cases}, \quad t = 1, \dots, 24$$

Next, the following constraints are introduced:

$$M \cdot y_t \geq x_{t,t}, \quad t = 1, \dots, 24 \quad (6)$$

Here $M > 0$ is a sufficiently large number. Constraints (6) ensure that if a cohort of size $x_{t,t} > 0$ is deployed at time t , then $y_t = 1$. Note that M is selected such that it exceeds any value $x_{t,t}$ may take. The number of cohorts, NC , is given by:

$$NC = \sum_{t=1}^{24} y_t \quad (7)$$

Our approach to generate a daily schedule of drones is to solve two problems sequentially, as follows:

We start by solving Problem A, defined as:

Minimize D subject to constraints (1), (2), and (5), where D is given by (3).

Problem A finds the least number of drones needed to complete the daily scanning load with the least flying time. Let D^* be the optimal solution. Form constraint (8) shown below:

$$\sum_{t=1}^{24} x_{t,t} \leq D^* \quad (8)$$

Next, solve Problem B, defined as:

Minimize NC subject to (1), (2), (5), (6), and (8), where NC is given by (7).

Problem B finds a solution that uses the least number of cohorts, where the least number of drones is deployed daily with the least flying hours. The solution should result in a schedule with minimal planning requirements.

9.3. Examples

To illustrate our approach, we will solve three examples in detail. The maximum flying time in these examples; $T = 10$.

9.3.1. Example 1

The second row of Table 3 gives the hourly demand for drones. The demand for drones starts at $t = 5$ and decreases as time increases. For this problem, the least flying time, $DF = 221$ drone-hour.

The solution of Problem A shows that $D^* = 27$ drones will be able to perform the daily scanning load. This solution results in 7 cohorts.

Next, Problem B is solved with 27 drones and 221 drone-hour, resulting in just two cohorts, the first starts at $t = 5$ and the second at $t = 15$. The complete solution is shown in the last two rows of Table 3.

If the demand for drones is either increasing or decreasing, then the cohorts will not overlap over time.

Table 3. Data and solution of Example 1.

t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$N(t)$	0	0	0	0	17	17	16	16	15	14	13	13	12	12	10	10	9	9	8	8	7	7	5	3
$x_{5,r}$					17	17	16	16	15	14	13	13	12	12										
$x_{15,r}$															10	10	9	9	8	8	7	7	5	3

9.3.2. Example 2

The second row of Table 4 gives the hourly demand for drones. The demand for drones starts at $t = 6$, and it increases steadily until $t = 13$, then decreases steadily. The least flying time, $DF = 205$ drone-hour.

Table 4. Data and solution of Example 2.

t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$N(t)$	0	0	0	0	0	13	13	14	15	16	16	17	17	12	12	10	10	9	9	7	7	5	3	0
$x_{6,r}$						13	13	13	13	13	13	13	13	9	9									
$x_{8,r}$								1	1	1	1	1	1	1	1	1	1							
$x_{9,r}$									1	1	1	1	1											
$x_{10,r}$										1	1	1	1	1	1	1	1	1	1					
$x_{12,r}$												1	1	1	1	1	1	1	1	1	1			
$x_{16,r}$																7	7	7	7	6	6	5	3	

The solution of Problem A gives $D^* = 24$ drones, 7 cohorts.

Next, Problem B is solved with 24 drones and 205 drone-hour, resulting in 6 cohorts. The solution is shown in the last six rows of Table 4. Note that the cohorts overlap in several time periods.

9.3.3. Example 3

The second row of Table 5 gives the hourly demand for drones. The demand for drones decreases for some time periods, goes up for others, then declines again. Here, $DF = 269$.

Table 5. Data and Solution of Example 3.

t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$N(t)$	0	0	0	0	0	17	16	16	15	14	13	13	14	15	16	16	17	18	19	20	15	10	5	0
$x_{6,r}$						17	16	16	15	14	13	13												
$x_{13,r}$													14	14	14	14	14	14	14	14	9	4		
$x_{14,r}$														1	1	1	1	1	1	1	1	1	1	
$x_{15,r}$															1	1	1	1	1	1	1	1		
$x_{17,r}$																	1	1	1	1	1	1	1	
$x_{18,r}$																		1	1	1	1	1	1	
$x_{19,r}$																			1	1	1	1	1	
$x_{20,r}$																				1	1	1	1	

The solution of Problem A gives $D^* = 37$ drones, and 9 cohorts.

Next, Problem B is solved with 37 drones and 269 flying hours, resulting in 8 cohorts. The solution is shown in the last eight rows of Table 5.

10. Summary and Conclusions

Innovation is at the heart of the technological response to the global COVID-19 pandemic. Adopting new safety procedures for handling materials as well as transferring tools and equipment between jobsites, prioritizing projects, adapting smart technology, and new tools and approaches in inventory management are all examples discussed in this study. The construction industry is experiencing rapid expansion of drone use, and the number of construction and engineering companies using drones has increased at an exponential rate and is expected to continue to grow. Design Engineers can create Building Information Models (BIM) and 3D renderings of a site using drone-obtained point clouds. Drones are already being utilized in every project life cycle. However, in the post-pandemic era we are witnessing a steep rise in automation in most capital projects. The benefits of using drones include improving productivity, reducing cost, and scheduling overruns on capital projects. The construction industry, with a reputation for being slow to adopt innovative technology, is now the biggest user of commercial drones and AI. Drones, modularization, and robotics are increasingly used on construction sites, fabrication shops, and for inventory control. With the ongoing trend, and the circumstantial statistics of the recent past, it will not be an exaggeration to declare that, in the near future, drones will be counted as required construction equipment such as trucks, cranes, and compressors.

The use of drones in the jobsite supply chain, like many innovative technologies, comes with many promises, yet there are presently profound limitations and big challenges in their application to the jobsite supply chain. Applications for the external use of UAVs are more limited than indoor use. Weather can play a key factor in the external use of UAVs. Cranes and other tall objects on site can interfere with automatic flight patterns. Battery technology is another factor limiting how long a drone can operate without recharging. Lastly, the FAA and OSHA both have stringent regulations on the use of drones on construction sites, long with all the legal questions. Recently, the FAA has provided some relief due to the pandemic, as well as the result of deregulation across many industries. However, technology is changing faster than the regulations. So far, the FAA regulations on the use of drones do not appear to apply indoors, which, in its present form, already faces obstacles concerning safety and security. Flying indoors has the risk of running into people, forklifts, crates, and other things. When it comes to flying drones indoors, it is recommended to have a lightweight base structure and propeller guards and the technological sense to stay away from ceilings and walls. UAVs, like other electronic devices, are exposed to many cybersecurity threats, including hacked servers, spied-on networks, and blocked communications. Regardless of whether drones are used indoors or outdoors, this poses a potential cybersecurity problem. UAVs can become a threat to our privacy and are used as spying devices. Therefore, companies need to take concrete security steps to prevent unwanted access and protect themselves from cyberattacks. The market size of the anti-drone market is expected to reach USD 1.85 billion by 2024, which proves the fact that significant efforts are being made to fight hostile drones [34]. Perhaps the biggest challenge in employing AI, drones, and construction modularization is reluctance to change on the part of contractors. Most contractors do not estimate the cost vs. benefits of using innovative techniques, especially if they have to invest more money on such ventures without seeing short term gains. Having the “owner” requirements and top management commitment on these issues will certainly help overcome the cost overruns.

This paper presented a Drone-Based Capital Project Optimization Model (DBCPOM) as an innovative tool for managing inventory on large capital projects in the post-pandemic era. The paper discussed the use of smart drones from the pre-planning phase to engineering, procurement, and construction. The use of smart devices and IoT allows warehouse managers to have real-time visibility of the location and progress of inventory that could potentially save thousands of hours on a major construction project. Wearable smart devices provide warehouse workers mobility in the warehouse. This enables them to access information remotely. The innovative drone technology project management teams can soon facilitate inspections in cost-effective and efficient ways. The data collected by drones

can give project stakeholders the opportunity to view a site in real time progression, help them better manage resources, and keep projects on schedule. This can improve future jobsite communication and collaboration between multiple onsite and offsite stakeholders and enhance planning. Veritably, the project manager can view a project without having to step foot on site.

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References

1. Deloitte Infrastructure & Capital Projects COVID-19 Response Portal “Impact of COVID-19 on Capital Projects, Construction Programs” A Proactive Response for Construction Planning, Design, and Management. [Online]. Available online: <https://www2.deloitte.com/us/en/pages/advisory/articles/impact-of-covid-19-on-capital-projects-and-construction-programs.html> (accessed on 26 May 2022).
2. Dronedeploy. Should We Prepare for a Construction Boom Post-COVID-19? 11 June 2020. [Online]. Available online: <https://www.dronedeploy.com/blog/should-we-prepare-for-a-construction-boom-post-covid/> (accessed on 4 May 2023).
3. DroneDeploy. The Construction Industry Is the Fastest Growing Adopter of Commercial Drones. 29 May 2018. Available online: <https://www.dronedeploy.com/blog/2018-commercial-drone-industry-trends> (accessed on 4 May 2023).
4. USA News Drones Business. U.S. Drone Regulations—Operations Over People Explained. 16 January 2023. [Online]. Available online: <https://www.suasnews.com/2023/01/u-s-drone-regulations-operations-over-people-explained/> (accessed on 4 May 2023).
5. Alrushood, M. Use of Drones and Emerging Technology in Megaproject Supply Chain. In *2020 AACE International Technical Paper*; ACCE: Chicago, IL, USA, 2020.
6. Rojas Viloria, D.; Solano-Charris, E.L.; Muñoz-Villamizar, A.; Montoya-Torres, J.R. Unmanned aerial vehicles/drones in vehicle routing problems: A literature review. *Int. Trans. Oper. Res.* **2020**, *28*, 1626–1657. [CrossRef]
7. Koshta, N.; Devi, Y.; Patra, S. Aerial Bots in the Supply Chain: A New Ally to Combat COVID-19. *Technol. Soc.* **2021**, *66*, 101646. [CrossRef] [PubMed]
8. Umar, T. Applications of drones for safety inspection in the Gulf Cooperation Council construction. *Eng. Constr. Archit. Manag.* **2020**, *8*, 2337–2360. [CrossRef]
9. Gutierrez-Franco, E.; Mejia-Argueta, C.; Rabelo, L. Data-Driven Methodology to Support Long-Lasting Logistics and Decision Making for Urban Last-Mile Operations. *Sustainability* **2021**, *13*, 6230. [CrossRef]
10. Han, D.; Lee, S.B.; Song, M.; Cho, J.S. Change Detection in Unmanned Aerial Vehicle Images for Progress Monitoring of Road Construction. *Buildings* **2021**, *11*, 150. [CrossRef]
11. Kim, S.; Kim, K. Systematic Tertiary Study for Consolidating further Implications of Unmanned Aircraft System Applications. *J. Manag. Eng.* **2021**, *37*, 03120001. [CrossRef]
12. Kim, K.; Kim, S.; Shchur, D. A UAS-based work zone safety monitoring system by integrating internal traffic control plan (ITCP) and automated object detection in game engine environment. *Autom. Constr.* **2021**, *128*, 103736. [CrossRef]
13. Shavarani, S.M. Multi-level facility location-allocation problem for post-disaster humanitarian relief distribution: A case study. *J. Humanit. Logist. Supply Chain. Manag.* **2019**, *9*, 70–81. [CrossRef]
14. Lambert. COVID-19: What Are the Long-Term Effects for the Construction Industry? 10 August 2020. [Online]. Available online: <https://onekey.milwaukeeetool.com/resources/blog/covid-19-long-term-effects> (accessed on 4 May 2023).
15. McKinsey & Company Capital Projects & Infrastructure. How Construction Can Emerge Stronger after Coronavirus. 8 May 2020. [Online]. Available online: <https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/how-construction-can-emerge-stronger-after-coronavirus> (accessed on 20 September 2020).
16. Riba Architecture. The Post Coronavirus Construction Boom: An Interview with Wang Liwei, China Development Foundation. 19 May 2020. [Online]. Available online: <https://www.architecture.com/knowledge-and-resources/knowledge-landing-page/interview-with-wang-liwei> (accessed on 19 May 2020).
17. Jreidini, R. Construction industry predictions for a post-COVID-19 world. *The Construction Specifier (CSI)*, 6 May 2020; News Section.

18. Asset Insight. Capital Project. 2013. [Online]. Available online: https://assetinsights.net/Glossary/G_Capital_Project.html (accessed on 25 September 2020).
19. City of Portland Budget Office. Definition-What Is a Capital Project? 25 September 2020. [Online]. Available online: <https://www.portlandoregon.gov/cbo/article/50495> (accessed on 4 May 2023).
20. Ernst & Young. *Spotlight on Oil and Gas Megaprojects*; Ernst & Young, Quarterly: London, UK, 2014.
21. Khan, S. An Analysis on Critical Causes of Delays in Oil & Gas Construction Projects. In Proceedings of the Project Management National Conference: Architecting Project Management for Redefining India, Bangaluru, India, 10–12 September 2015.
22. Burger, R. Beginner's Guide to Using Drones for Construction Management. *ConTech Academy Autodesk*, 15 August 2019.
23. Construction World. 7 Ways Robotics is Transforming the Construction Industry. *Construction World*, 6 February 2017.
24. Winick, E. AI and drones are being used to control construction projects. *MIT Technology Review*, 15 March 2018.
25. Bechtel Newsroom. Bechtel among First Companies to Use Unmanned Aircraft System Technology in Construction. Bechtel, 6 April 2015. [Online]. Available online: <https://www.bechtel.com/newsroom/releases/2015/04/unmanned-aircraft-system-technology-construction/> (accessed on 18 December 2019).
26. Song, J. Tracking the location of materials on construction job sites. *J. Constr. Eng. Manag. ASCE* **2006**, *132*, 911–918. [CrossRef]
27. Trebilcock, B. The emerging role for warehouse drones in the supply chain. *Modern Materials Handling*, 13 July 2018.
28. TNB News. Renault starts using drones inside truck factory. *SMMT Newsletter, England & Wales*, 3 April 2019.
29. Kim, C. *Development of Automated Pipe Spool Monitoring System Using RFID and 3D Model for Plant Construction Project*; Korean Society of Civil Engineers: Seoul, Republic of Korea, 2012; pp. 865–876.
30. Song, L. Early Contractor involvement in design and its impact on construction schedule performance. *J. Eng. Manag.* **2009**, *25*, 12–20. [CrossRef]
31. Edwards, D. Robotics & Automation. Collaborative Robots Working with Human Welders in Manufacturing, Says Novarc. [Online]. Available online: <https://roboticsandautomationnews.com/2019/08/21/collaborative-robots-taking-over-from-human-welders-in-manufacturing-says-novarc/25116/> (accessed on 21 August 2019).
32. Song, J. Field Trials of RFID Technology for Tracking Prefabricated Pipe Spools. In Proceedings of the 21st ISARC, Jeju, Republic of Korea, 14–15 September 2004.
33. Rahbar, F. PS.05: Rapid Recovery from Schedule Slippage (RRSS). In Proceedings of the AACE 54 Annual Transaction, Atlanta, GA, USA, 27–30 June 2010.
34. Flyvbjerg, B. *The Oxford Handbook of Megaproject Management*; Oxford University Press: Oxford, UK, 2017.

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