Article

The Creation of Construction Schedules in 4D BIM: A Comparison of Conventional and Automated Approaches

Omar Doukari [1,*] , Boubacar Seck [2] and David Greenwood [1]

1   Digital Built Environment Research Group, Northumbria University, Newcastle-upon-Tyne NE7 7YT, UK; david.greenwood@northumbria.ac.uk
2   Centre de Paris-Nanterre, CESI Ecole d'Ingénieurs, 92000 Nanterre, France; bseck@cesi.fr
*   Correspondence: omar.doukari@northumbria.ac.uk; Tel.: +44-(0)191-227-3006

Abstract: Building Information Modelling (BIM) is now a globally recognised phenomenon, though its adoption remains inconsistent and variable between and within the construction sectors of different countries. BIM technology has enabled a wide range of functional applications, one of which, '4D BIM', involves linking the tasks in a project's construction schedule to its object-orientated 3D model to improve the logistical decision making and delivery of the project. Ideally, this can be automatically generated but in reality, this is not currently possible, and the process requires considerable manual effort. The level of maturity and expertise in the use of BIM amongst the project participants still varies considerably; adding further obstacles to the ability to derive full benefits from BIM. Reflecting these challenges, two case studies are presented in this paper. The first describes a predominantly manual approach that was used to ameliorate the implementation of 4D BIM on a project in Paris. In fact, there is scope for automating the process: a combination of BIM and Artificial Intelligence (AI) could exploit newly-available data that are increasingly obtainable from smart devices or IoT sensors. A prerequisite for doing so is the development of dedicated ontologies that enable the formalisation of the domain knowledge that is relevant to a particular project typology. Perhaps the most challenging example of this is the case of renovation projects. In the second case study, part of a large European research project, the authors propose such an ontology and demonstrate its application by developing a digital tool for application within the context of deep renovation projects.

Keywords: 4D BIM; construction scheduling; project planning; building renovation; automation; ontology; artificial intelligence; lean methodology

1. Introduction

The construction sector has undergone many technical and regulatory developments over recent decades. Concerned about the impact of their projects on the environment and the safety of end-users and other project stakeholders, project owners have become more and more demanding when it comes to commissioning projects [1]. However, those involved in construction have, according to some commentators, changed their working methods very little [2]. This gap between changes in rules and standards that affect the demand-side, and the relative stagnation of those on the supply-side, has significant impacts on the duration, cost and quality of the works delivered. A project is an environment where stakeholders with different profiles are required to achieve specific objectives. The success or failure of a project depends on the strategy adopted to organize, coordinate, and supervise all the activities and works that need to be scheduled and then delivered while taking into account the various internal and external project constraints [3].

The planning and scheduling of construction projects represents an important part of the management of the construction process. It plays a crucial role in a project's success, since it facilitates the allocation of resources (such as equipment, materials, and labour)

to project activities over time, to ensure the completion of the project on time and within budget [4]. In addition to determining the pace of the work, good scheduling enables project stakeholders to check project feasibility, estimate the preliminary costs, maintain safety, optimise the use of resources, and allow the project team to monitor and control progress and determine if the work is proceeding efficiently, ensuring that the client's objective is achieved [5]. Furthermore, planning and scheduling deficiencies [6] and poor communication among project participants [7] have been identified as major factors that can lead to project delays and cost overruns, and ultimately to claims and disputes [8]. As a major contributor to the global economy (13% of global Gross Domestic Product) and one that is expected to rise by 85% to \$15.5 billion globally by the year 2030 [9], the construction sector is still under-achieving and inefficient, since 9 out of 10 global mega projects encounter delay and cost overruns [10]. Scheduling software packages, such as Primavera and Microsoft Project [11], as well as planning techniques such as bar charts, time charts, and network approaches, are used to assist and help project managers in planning construction projects [12]. However, these tools are still limited and insufficient when considering the massive amount of newly-available data (e.g., feedback, images captured from smart devices, IoT sensors, etc.) that can continuously be produced on every project. Effective use of these data could enable valuable insights through a combination of Building Information Modelling (BIM), Artificial Intelligence (AI) and Machine Learning (ML) [13].

The advent of BIM has changed the practice of project management and has assisted project managers in expediting their duties more effectively than they have in the past. BIM can be defined as a set of tools, processes, and technologies that are enabled by a digital representation of the physical and functional characteristics of a built asset [14] expressed in data-enriched 3D models and their relationships. This digital replica constitutes a shared and central source of data about a facility, forming a reliable basis to produce information that supports insightful decision making for planning and managing a construction project throughout its entire life cycle [15]. Such information could include onsite spatial and topographical information, temporal and schedule information, and resources and cost information, among others [16–18]. BIM models are characterised by a level of development (LoD) which varies from 100 to 500 (i.e., from least to most developed) and serves to specify the appropriate amount of information required for specific uses [19]. Such digital representation is multi-dimensional, or 'nD', where each dimension indicates an information-processing capacity for various aspects [20]. The fourth dimension, known as 4D BIM, incorporates time-related information in the 3D information model to simulate and optimise the project construction process [21]. Practically, this consists of linking units of work or elements in the form of objects from the geometric 3D model to the construction scheduling activities using proprietary software, such as Navisworks or Synchro Pro [22,23]. Beyond the fifth dimension, understood as cost-estimating capacity [24], there appears to be lack of consensus [25].

Research has shown that 4D BIM can be a solution to overcoming many deficiencies of current planning practices [26]. The enrichment of a 3D BIM model with scheduling data has increasingly improved the quality of the construction planning process through the development and integration of several use cases, such as dynamic site analysis with temporary components including equipment movement, resource availability, the management of congestion and other operational constraints [27–29], spatiotemporal analysis for health and safety management [30,31], evacuation path planning [32], logistics management [16], augmented vehicle tracking and transportation route planning [33], construction waste management [34], spatial conflict detection and workspace congestion avoidance [16], and the monitoring of construction progress with site layout designs [35,36]. Overall, according to Candelario-Garrido et al. [37], 4D BIM simulation is 40% more efficient than conventional planning procedures. Furthermore, 4D-BIM-based visualisations provide an intuitive comprehension of the construction process which enables more effective communication and therefore better collaboration between all project stakeholders [38,39].

Although the benefits of 4D BIM are clear and much reported in the literature, few studies have considered the actual implementation of such tools and the corresponding processes during the construction phase that involves many actors. The use of 4D BIM is currently only adapted for small projects with few activities, since its use can be very expensive and time- and effort-consuming [23]. Moreover, there is little research addressing how 4D BIM can best be coupled and used with AI tools; e.g., to optimise and develop more effective strategies for construction project management through the automatic generation and simulation of different construction scenarios [40]. To bridge this gap, this study first presents case-based evidence of the use of 4D BIM during the construction phase of a real project to understand how this tool can be practically implemented to support and assist the project participants in their mission. Second, to enable process automation and 4D tools development, this paper presents an ontology—known to be a useful AI tool in formalising specific domain knowledge including concepts, relations, and constraints [41,42]—dedicated to scheduling, planning, and 4D simulation, and demonstrates its application by populating the corresponding database and developing a digital tool for application within the context of deep renovation projects that are part of a large European research project known as the RINNO project.

The remainder of the paper is organized into five parts. After a brief review of planning in construction projects in general, Section 2 reviews the literature on the use of 4D BIM, concluding in the identification of remaining barriers and problems for investigation. In Section 3, the sources of empirical and theoretical data are introduced. These include a literature review of 4D BIM applications and a survey of 4D BIM practice in France. The construction of a new building at the CESI campus in Nanterre-Paris prompted the overall study of a newly proposed approach to the process of 4D BIM implementation, which is detailed in Section 4. The proposed method is then demonstrated on the Nanterre 2 CESI Project in Section 5. The ontology proposed, along with a digital tool to automate the process of 4D BIM simulation specifically dedicated to scheduling of renovation projects, is introduced in Section 6. The CESI 4D BIM methodology was applied under unique circumstances and its more general applicability to the construction industry is discussed in Section 6 alongside the RINNO project case study, and the future work envisaged by the research team. The content is summarised in Figure 1, below.
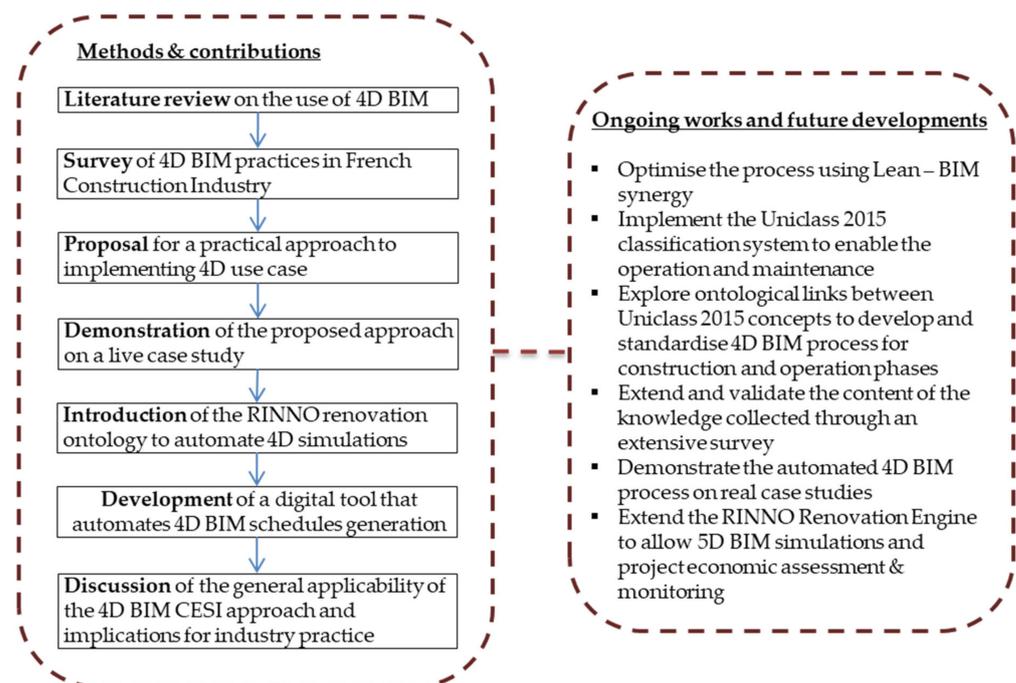

Figure 1. Methods, contributions, ongoing works, and future developments presented in this study.

2. Planning of Construction Projects

The ISO 21500 standard defines a project as "a unique set of processes consisting of coordinated and controlled activities with start and finish dates, undertaken to achieve an objective" [43]. In order to achieve these deliverables, the processes comprise a set of activities to which human, financial, and material resources are allocated. These activities are also limited in time. The total duration of the project is the sum of the durations of those activities that are 'critical' (i.e., those in which a delay would cause a comparable delay in the completion of the project [44]). The definition given by the standard [43] also addresses the importance of the constraints that may be external to the project (regulations, socio-economic situations, environmental issues, etc.) or internal (the availability of resources, the degree of skill of the actors, budget envelopes, etc.). A project is also characterized by a life cycle in which each of the stages requires the implementation of groups of processes to organize and control the work of the stakeholders in order to achieve the initial objectives. This life cycle depends on the nature, size, and field of activity, as well as the constraints of the project. Project management consists of identifying, planning, and controlling the processes required to increase the probability of the project's success at each phase of the life cycle.

2.1. Construction Project Management

The construction sector brings together all the activities of the design, construction, operation, and demolition of public works, civil engineering, and building works. The vast majority of construction projects follow a sequential development where each of the stages corresponds to a phase of the project. There are four main phases covering the life cycle of a built asset: Pre-project, Pre-construction, Construction, and Post-construction [45]. At each stage of the project, different actors are needed to plan, execute, and control the activities. The complexity of construction projects lies in their rapid pace [46], their unique environment (regulations, location, type of market, etc.) [47] as well as the multiplicity of stakeholders with different roles and periods of intervention [48].

To successfully manage a project, effective planning in all its phases is essential. The corresponding tools and methods can be counted by the dozen, and they must be adopted and put into practice by all of those involved in the construction industry in order to facilitate coordination and time control [49]. The most commonly used tools and methods are detailed in the next section.

2.2. Planning Methods for Construction Projects

2.2.1. Traditional French Job Titles and Planning Process

Planning a construction project involves identifying, for each stage of the project, the activities to be carried out in order to achieve the desired objectives. The activities must then be broken down into elementary tasks so as to be scheduled with respect to the technical, economic, and specific constraints of the project. By doing so, the resulting deliverable makes it possible to clearly explain the detailed progress of the project, while validation milestones ensure the measuring of progress and the quality of the services to be performed.

In a construction project, a schedule is developed by the client, noting the project's feasibility. This preliminary schedule rarely details each of the project tasks because many of them are still unknown or might be deleted and/or modified. However, it enables a quick assessment of the project duration in its early stages, despite a significant degree of uncertainty. To respond to project tenders, bids are expressed using the envelope planning of the project owner (in French the maître d'ouvrage, or MOA) as input. The granularity of tasks is reduced to make improvements and confirm or reject the initial duration expectations. Finally, before the construction phase, companies must also create execution schedules based on the general planning of the project entity in charge of the implementation of the project (the company, firm, department, or person called in French the maître d'oeuvre, or MOE). These schedules take into account their ability to mobilize

the necessary resources, delivery times for supplies, and scheduling constraints that link them to other onsite activities [50].

As the activities of all project participants are strongly interconnected in time and space, it is fundamental to collaborate throughout the whole project in order to reduce the impacts of potential causes of delay. This is precisely the role of the scheduling, management, and coordination team (in French the Ordonnancement, Pilotage, Coordination or OPC); to bring together and synchronise all the schedules as well as to be the unique contact for project participants to coordinate activities in case of any conflicts or problems. Depending on the nature and context of the project, the OPC may implement and use different planning methods. It should be noted that, in this paper, although generic role descriptors have been used where possible, occasionally it has been necessary to use French job titles. These, and their English equivalents, are provided in Appendix A, Table A1.

2.2.2. Planning Methods

Several classes of scheduling methods have been identified through the review and analysis of various literature concerning construction planning [51]. The most known and used are (a) the Critical Path method, (b) the Line-of-Balance method, (c) the Program Evaluation and Review Technique (PERT), (d) simulation methods, (e) AI-based methods, (f) visualisation methods, (g) Critical Chain scheduling, (h) location-based scheduling, and (i) Lean methods. These are detailed in the following paragraphs.

(a) The Critical Path method was first used in the 1950s in the United States [52]. It is most used in construction projects since it is easily applicable to sequential projects. However, it has many drawbacks, the most important of which is the use of ratios derived from feedback. Therefore, whether the duration of the tasks is under- or overestimated, this method does not leave the freedom to the actors to easily adjust their schedule to the pace of the actual production.

(b) The Line-of-Balance method was first created by the Goodyear Company in the early 1940s [53], before being adopted and developed by the U.S. Naval Forces in the early 1950s [54]. It is a powerful tool used for scheduling and controlling construction projects that contain repetitive blocks of activities, such as high-rise buildings, roads, tunnels, railways, and pipelines. Its focus is on resource allocation for each construction phase so that activities are achieved in time without any interference from the following phases [53].

(c) The PERT method was also developed by the U.S. Naval Forces. It has the advantage of making the scheduling of tasks more flexible [55]. The PERT method is based on the calculation of total margins and free margins that will enable the OPC to easily evaluate their degree of freedom to modify activity dates in the case of any hazards or to optimise space and resource allocation. Although it allows some flexibility compared to the Critical Path method, the PERT method inherits from it several disadvantages, in particular the absence of indications on the occupation of space or the allocation of resources.

(d) Simulation methods [56] are powerful tools [57,58] that have been developed and used during the last 60 years in construction to enable project managers to optimise project resources and improve productivity [56]. However, only repetitive or cyclical construction activities could be simulated [56].

(e) AI-based scheduling techniques have been used in construction since the 1980s [59]. They allow project managers to automatically generate optimised schedules based on different scenarios and AI algorithms [60–63]. However, representing and integrating uncertain knowledge while generating onsite construction schedules is still the main weakness of these methods [51].

(f) Since the 1990s, several visualisation methods [64] and technologies (BIM [65], VR [66], AR [67], MR [68]) have been developed in construction to improve communication between project participants and enhance the visualisation and validation of the construction plans.

(g)   The Critical Chain method [69] complements the impact of variation within a construction project by introducing the concept of buffer. It aims to reduce contingencies and allows project managers to take into account the limitations of resources when developing project schedules through the insertion of aggregated buffers.

(h)   The location-based scheduling method is used mainly for projects where the activities have to be repeated many times (high-rise buildings, collective housing, linear infrastructure, etc.). It is a spatiotemporal representation of a project that focuses on the rate of production capacity of each team. A grid is used to describe the duration and location of each task. The space is represented on the ordinate by means of different points of the project; the starting point, the ending point, as well as specific points between (floor numbers, kilometre posts, intersections, structural work, etc.) [70]. Although it enables the checking of the production rate while taking into account the use of site space, the implementation of this method requires time and advanced planning skills.

(i)   Lean methodology is based on a production philosophy which originated in the automobile industry [71]. The aim of Lean-based planning methods [72] is to continuously improve the added value of the construction tasks (performance, cost, quality, and duration), with the goal of enhancing the overall profitability of the project. In the construction domain, nine Lean planning and control techniques have been identified [73]. Based on several planning levels (Master, Phase, Look-ahead, Commitment), the Last Planner method [74] is one of the most used and implemented Lean techniques in construction [75–78]. This method focuses on short-term planning at crew level. Generally, Lean methods are implemented using a support (standard or digital board) on which the actors indicate the nature, location, and type of material to be mobilized, as well as the number of workers required to execute the task. This is repeated weekly in order to study the interdependencies of the tasks, prevent possible conflicts, and collectively propose optimisations. The main advantage of this method is that it takes into account the needs and constraints of each project actor by promoting and encouraging collaboration before task executions. Stakeholders combine their knowledge and effort for the general interest of the project and not just to achieve their own activities and objectives. As for any collaborative work, this method requires the real involvement of all the project stakeholders, along with rigorous and constant participation.

2.3. Problems for Investigation

Clearly, it is up to the project team to choose the most suitable planning method with respect to the project context and the level of expertise of the project stakeholders. However, despite the fact that these methods have been used for decades, it should be noted that few construction projects have succeeded in achieving their initial objectives in terms of cost and duration [79]. Furthermore, traditional planning methods are very limited and unsuitable when considering the massive amount of data that the construction industry is producing on a daily basis over many construction projects. This knowledge base could be used to enable stakeholders to gain useful insights by using BIM and AI tools, as outlined by Gondia et al. [13] in their survey. Consequently, construction actors are increasingly adopting IT-based tools to develop more comprehensive, flexible, and efficient construction and planning methods, such as those based on BIM [80].

3. Construction Planning and the Advent of 4D BIM

BIM makes it possible to design, build and operate a structure over its entire life cycle [14]. It involves a collaborative process within the company and between external partners around a digital model. The latter can be described as a 3D representation of the physical and functional characteristics of a built asset [81]. It is a technical database, made up of objects defined by their characteristics and the relationships between them. The whole forms a structured set of information about a built asset. The 3D model is useful

for visualizing the planned project. However, on its own, this virtual structure remains static and does not allow a clear appreciation of the implementation of the construction process and the dynamic that characterises the sequence works. To make it dynamic, it is necessary to integrate a fourth dimension: time. This is the principle of 4D planning. In practice, this corresponds to linking the 3D elements of the BIM model with the project schedule activities. The next two subsections review the different applications and use cases in which 4D BIM has been used so far, and present a survey about the most-used 4D BIM tools, practices, and methods in France.

3.1. Review of 4D BIM Applications

Research has shown that 4D BIM can be a solution to many of the deficiencies of current planning practices [26]. The enrichment of a 3D BIM model with scheduling data has increasingly improved the quality of the construction planning process through the development and integration of several use cases. For example, simulating the progress of work over time is an efficient communication tool for explaining to a client the progress of a project and the construction methods used. Indeed, 4D-BIM-based visualisations provide an intuitive comprehension of the construction process, which enables more effective communication and thereby better collaboration between all project stakeholders [38,39]. The use of 4D BIM has made several applications possible, including the following:

(i) **Site analysis including temporary components** such as equipment movement, resource availability, the management of congestion, and other operational constraints. Construction project productivity can be decreased by about 65% due to space congestion [82]. For instance, Huang et al. [29] proposed the integration of construction virtual prototyping systems with 4D models to provide realistic graphical simulations that incorporate both the layout and dynamic analysis of the construction site.

(ii) **Spatial conflict detection and workspace congestion avoidance.** Chavada et al. [83] analysed conflict detection between workspaces using a 4D BIM visualization of construction schedules. Moon et al. [17] developed an active simulation system based on 4D models and an optimisation process to minimise the simultaneous interference level of the schedule workspace. Trebbe et al. [84] explored the use of 4D models to coordinate different construction engineering designs, schedules, and the operations of contractors on a real railway station renovation project.

(iii) **The monitoring of onsite construction work progress with site layout designs.** Tran et al. [85] explored the use of 4D BIM and a visual programming language to develop a conceptual framework of camera planning that enables the monitoring of construction site progress. To detect deviations in the construction process between the actual state of a construction and its planned state, Braun et al. [86] proposed an automated framework based on photogrammetric surveys and 4D BIM models.

(iv) **The production of short-term work plans.** Sriprasert and Dawood [87] implemented a visual multi-constraints planning framework based on the use of 4D BIM and Lean methodology principles. The LEWIS system enables the integration of construction-related information and constraints with 4D planning to ensure the generation of constraint-free commitment work plans.

(v) **Spatial–temporal analysis for health and safety management.** To prevent construction accidents, Tran et al. [30] proposed a hazard identification approach based on spatial–temporal conflicts that may lead to accidents using 4D BIM models. Han et al. [88] proposed the 3D-CES system to design, verify and simulate the 3D visualisation of mobile crane operation. To assist in elaborating the crane lift schedule, this system enables the identification of safety and productivity aspects while selecting the most efficient crane operation. Tan et al. [89] investigated the use of BIM and 4D acoustics simulation tools to mitigate the noise impact on maintenance workers of offshore platforms. In this framework, the BIM model was used as a source of information, whereas the 4D acoustics approach was used to provide the spatial–temporal sound pressure level distribution of the generated noise;

(vi) **Evacuation path planning.** Kim et al. [32] proposed a 4D-BIM-based framework that automatically analyses, generates, and visualises the evacuation paths of workers. The prototype developed takes into account construction activities and site constraints to enable the identification of accessible evacuation paths considering customised parameters, such as workspaces, temporary structures, and storage areas.

(vii) **Logistics management.** For example, to facilitate the visualisation and analysis of construction progress and workspace logistics, Golparvar-Fard et al. [90] proposed the use of 4D photographs. Said and El-Rayes [91] developed an automated multi-objective construction logistics optimisation system to integrate and optimise material supply and site layout decisions. Chin et al. [92] proposed a framework to support the logistics and progress management of structural steel works by using 4D with radio frequency identification technology.

(viii) **Augmented vehicle tracking and transportation route planning.** Chen and Nguyen [33] investigated the use of BIM with a web map service for selecting between construction material sources. The BIM–WMS decision-making system developed was based on the evaluation of the final cost, material delivery time, and location credits to help designers and project managers in the selection of materials, and cost and schedule planning.

(ix) **Construction waste management**. Hewage and Porwal [93] proposed a 4D-BIM-based framework in order to predict material waste and propose recycling strategies in construction. Won and Cheng [94] developed a 4D BIM construction waste estimation system which relies on construction waste factors for the estimation of waste generation. Bakchan et al. [95] presented a theoretical 4D BIM solution for construction waste disposal scheduling. However, according to Guera et al. [34], existing 4D BIM applications for construction waste management present some deficiencies, such as only focusing on waste generated by rework activities, a lack of estimation for off-site recycling, and/or the use of fixed factors. To overcome these issues, they proposed the integration of temporal-based algorithms with 4D BIM and demonstrated the proposed solution on two different case studies located in North America for the case of concrete and drywall waste reuse and recycling planning [34].

Furthermore, Candelario-Garrido et al. [37] have investigated the general benefits of using 4D BIM simulation for the construction industry and have estimated this tool and corresponding approaches to be 40% more efficient than conventional planning procedures. Linking the digital model to the construction schedule allows project managers to identify planning errors [39] given that 70% of traditional schedules produced are wrong and non-optimised [96]. Non-compliance with a schedule has a direct effect on the duration and costs of the work as well as possible indirect effects on its quality [97]. Extending incorrect schedules usually disrupt the smooth execution and coordination of works, and companies must use additional resources and accommodate the new activities within a very short time.

Despite the clear benefits of 4D planning methods, examples of their adoption, use, and application on real projects are rarely documented. Several research works propose 4D planning methods based on the development of specific and bespoke workflows requiring an advanced level of expertise in using many computerisation tools in different specialisation domains [98]. In addition, the use of 4D BIM is currently only adapted for small projects with few activities, rather than very expensive, time- and effort-consuming projects [23,31]. This is mainly due to the complex nature of 4D planning methods which are usually defined and based on interfacing BIM authoring tools (e.g., Revit, ArchiCAD, Bentley), BIM management tools (e.g., Navisworks, Syncro Pro), and legacy scheduling tools (e.g., Primavera, MS Project). There exists a lack of interoperability between the three groups of tools, since BIM authoring platforms are usually more suited to the design stage [23]. In particular, because of this lack of interoperability between BIM tools and BIM management platforms, the modification of any activity or 3D element generates a lot of manipulations, adjustments, and repetitions of the 4D planning process. Moreover, there is

a dearth of studies that investigate how 4D BIM can be integrated with AI tools which will enable the development of more effective methods for construction project management by considering the massive amount of data produced on every project and thus enable the gaining of valuable insights [40].

To capture the industry perspective on BIM-based 4D solutions and understand existing practices, a survey of French construction companies was performed. The results of the survey are described in the next subsection.

3.2. 4D BIM Tools and Methods Used in France

A questionnaire survey was conducted in order to understand 4D BIM practices in France. The questionnaire was first designed then shared online on professional platforms, such as LinkedIn, to allow construction companies to complete it and share their experience and practices. It consisted of three main items: (i) the 4D planning tools used by the company and why (advantages and disadvantages), (ii) the strategy and methods used to implement these tools, and (iii) the different use cases and applications for which these tools were used. The survey was conducted remotely from February to April 2020. Fifty-one participants, including BIM managers and experts from different French construction companies with different backgrounds and specialisations, such as architecture, civil engineering, construction informatics, and project management, received and completed the survey.

As shown in Figure 2, Navisworks and Synchro Pro are the most widely-used BIM-based 4D planning softwares in France with 55% and 25%, respectively. Other 4D planning tools, such as Vico Control (6%), XD Builder (4%) and others (e.g., ITwo 4.0) are used by some French construction companies as well. However, not all the respondents had experienced the use of 4D BIM planning (6%), which demonstrates that the 4D BIM tool is not yet fully implemented and adopted within the French construction ecosystem.
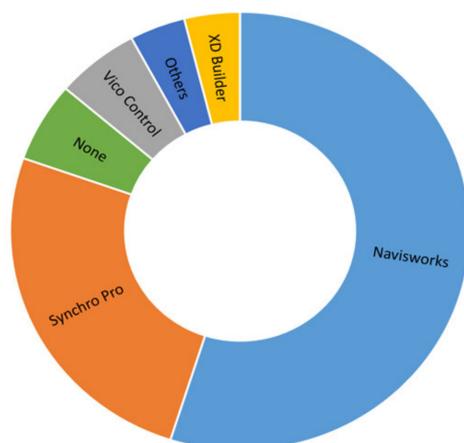
Figure 2. Most used 4D BIM tools in France.

The most used 4D tool in France is Navisworks. It is easy to use and enables the linking of activities on a bar chart to corresponding 3D elements in the BIM model. Navisworks can be used for operation control, conflict analysis, construction sequences, and coordination between disciplines. However, this tool requires many manipulations of the BIM model and planning to integrate changes. In addition, to ensure consistency between these two entities (i.e., BIM and planning), it necessitates the adoption of a relevant LoD. The second most popular 4D tool in France, according to the survey, is Synchro Pro. It integrates some planning functionalities and so enables an integrated planning process performed in the same interface as the 4D simulation. However, this tool is still difficult to learn and therefore to implement on construction projects. Compared to Navisworks, it requires more time and practice before project managers can handle it correctly. Indeed, the planning method used by Synchro Pro seems to make the study of spatial constraints more difficult.

The activities are defined with respect to their locations, which generates a huge number to manipulate and deal with, in addition to their logical and resource links.

The survey showed that two strategies exist for setting up the 4D planning use case. The first is a real implementation which consists of identifying the needs in terms of 4D planning, selecting the most suitable software by acquiring a license, and finally, developing a training plan to master the corresponding tools and methods. The second strategy to implement 4D planning on a construction project is to outsource this use case by subcontracting it to another engineering company that will use its own solution and methods. This article takes part in the first strategy by proposing a method that allows construction companies to initiate and internally implement 4D planning works for any projects.

However, the results revealed that the use of 4D planning is still limited and mainly restricted to creating and simulating 4D project videos to communicate internally within the same company and/or with the client. These video animations are usually non-interactive and disconnected from the progress of actual onsite works. However, some big contractors, such as Vinci Construction France or Bouygues Construction, have good expertise in 4D planning, and they use it for advanced applications, such as project progress monitoring and control, and employ digital tools that allow site workers to provide daily information on the quantity of tasks performed. The use of these data enables project managers to evaluate onsite production, monitor and control progress, and make the appropriate adjustments to the 4D planning if necessary [16].

Furthermore, the survey highlighted two methods used by the French companies to implement 4D BIM. The first method is based on the 'Hardin and McCool method'. This method [96] is the most commonly used because it applies the basic 4D principle of linking a schedule to a digital model. Indeed, it proposes a solution based around the Navisworks software and its TimeLiner module. By importing a Gantt schedule and a digital model of a project, it is possible to link the corresponding digital objects to each of the project tasks. This link can be performed manually or automatically if the 4D parameters of the digital model have been correctly created and entered. The second method is developed by the iBIM teams at the Vinci Construction France company. This method is based on the use of Synchro Pro software. It consists of remodelling and restructuring the BIM model into elementary objects, creating a task for each item in the schedule, and then linking each elementary object to its corresponding task. This results in a 4D schedule with a very high granularity, since the BIM objects in the original BIM model will be split into many new elementary BIM objects according to their actual onsite construction schedule. For example, an existing slab object (or any other element, such as a floor or wall) within the original BIM model could be split into more than one elementary slab in the new restructured BIM model to be suitable for the 4D planning method. Although this solution allows for the precise planning of the schedule, its main drawbacks come from its highly detailed breakdown. The implementation of this method represents a manual, laborious, and time-consuming process of restructuring and reorganising all the BIM model elements of the built asset. For instance, according to an iBIM's BIM manager, a structural BIM model for a medium-sized project (~10M €) includes more than a thousand elementary building components. Therefore, even if the laborious data restructuring work of the BIM model has been carried out in advance, it is relatively complicated for onsite teams to quickly identify the work in progress and indicate the level of progress.

3.3. Summary of the Identified Problems

The difficulties encountered by survey respondents corresponded closely with the observations noted in the literature, summarised in Section 2.3, above. This suggests that current methods of creating 4D tools from 3D BIM models are either (i) relatively easy but not suitable for the full range of construction site planning functions (as in the case of the Hardin and McCool approach); or (ii) reasonably suitable for such purposes in terms of their granularity but involve a laborious and time-consuming manual conversion process.

The requirement for the CESI BIM team to undertake the implementation of 4D BIM planning on the Nanterre 2 project presented an opportunity to develop a workflow that addressed these concerns. The aim was to produce an approach to 4D BIM implementation that could produce a construction schedule of maximum functionality with minimum extra effort expended in data exchange. The results, which are presented in the following section, could help project participants more fully exploit the potential of 4D BIM.

Furthermore, to address the problem of how 4D BIM can best be coupled and used with AI technologies to exploit the massive and increasing amount of construction data and enable 4D BIM automation, Section 6 proposes an ontology and demonstrates its application by developing an automated 4D BIM process for application within the context of the RINNO research project.

4. A New Proposed Methodology for 4D BIM Planning: The CESI Process

The previous sections and literature reviews on construction project planning generally and 4D BIM methods in particular were used as a starting point for understanding the construction industry's needs and then developing the CESI planning process. The purpose of this method is to identify and develop all the steps to be followed to guarantee the achievement of the MOA objectives concerning 4D planning. Following a four-phase process (Figure 3), the CESI method details how this BIM use case should be required and specified by the client until the production and delivery of related deliverables. This solution is intended to be simple and pragmatic. The following subsections detail the different phases of the CESI method.
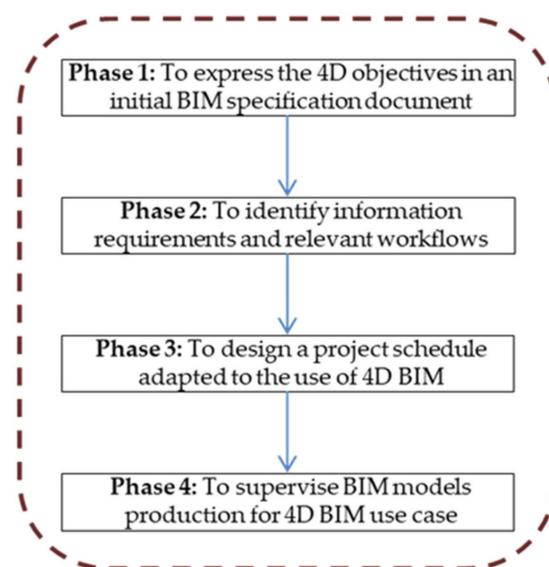
Figure 3. The CESI 4DBIM approach.

4.1. Phase 1: To Express the 4D Objectives in an Initial BIM Specification Document

The first actor in the project that allows the implementation of BIM is the client. Their role is to express needs which can be explicit, implicit, precise, or vague, depending on their familiarity with construction techniques and rules. However, the client can be supported by an assistant project manager (in French the assistant à maîtrise d'ouvrage, or AMO) who will help to precisely define the client's needs and achieve their strategic objectives. The method proposed recommends the use of SMART objectives (Specific, Measurable, Achievable, Realistic and Time-bound) for each of the BIM use cases desired by the client. For the 4D BIM use case, several SMART objectives can be expressed by the client. For the 4D BIM use case, examples of such SMART objectives are:

- The contractor's response to the invitation to tender must include 4D planning of construction methods for the works in a visual form that demonstrates its feasibility.

- The appointed contractor's BIM manager is responsible for the provision of a 4D schedule for the construction phase and its submission to the client. This must allow for progress monitoring of the works at any time during their execution and include the work of all the project delivery team.
- The contractor's 4D planning solution must enable the identification of all co-contracting zones during the progress of the works with the objective of ensuring and optimising the safety of the site staff and operatives of the companies involved in the works.

This formulation of 4D planning objectives makes it possible to explicitly identify the client's expectations. In this case, the BIM manager will be able to propose detailed solutions to organise the production of BIM models that enable this use case implementation.

4.2. Phase 2: To Identify Information Requirements and Relevant Workflows

The BIM manager precisely determines all the parameters to be taken into account and integrated into the 4D planning. This preliminary work is important because it helps explain to project contributors how to adapt their traditional deliverables (schedules and models) in order to be usable within the framework of 4D planning. As such, the BIM manager can proceed in three steps as follows:

Step 1: To convert the client's objectives into SMART objectives if this has not been carried out in the specification document. Indeed, non-SMART goals are often open to interpretation, unfeasible, or incomplete.

Step 2: To determine what information must be produced to perform relevant 4D planning. When the 4D objectives require expertise that is beyond those of the BIM manager (e.g., environmental risk management), project actors, such as QSE (Quality Security Environment), CSPS (Construction Safety and Health Protection Coordination), and specialised BET (an engineering company), should be appointed by the client at the request of the BIM manager.

Step 3: To draw up a functional and pragmatic strategy and formalise it in the BIM Execution Plan (in French the convention BIM). Indeed, to share and use the identified information, a workflow must be put in place to specify: what digital tools are capable of exploiting the information; in which formats the information should be delivered; how the information should be produced, controlled and shared; and finally, what deliverables are expected.

4.3. Phase 3: To Design a Project Schedule Adapted to the Use of 4D BIM

To ensure quality, optimal coherence, and consistency between the BIM model(s) and the construction schedule, a working method is formalised, as follows:

Step 1: The provisional or final construction schedule (depending on the stage of the project) is obtained. This schedule will be the input to the design process described below.

Step 2: The MOE, OPC, and CSPS meet to study the general planning of the project and identify the phases that could represent health and safety risks for the project (e.g., complex construction methods, areas of high co-contracting, significant environmental risks, heavy traffic flow).

Step 3: Meetings are held as necessary between the OPC, contractors and project actors to study in detail the scheduling of tasks. The synthesis of all this information will make it possible to propose a preliminary solution that will then be integrated into the 4D BIM use case and using visualisation, will then be validated or amended.

Step 4: The OPC in charge of monitoring and coordinating the work must master traditional planning and 4D BIM based planning tools, because they are in charge of linking the planning to the BIM model. The BIM manager is also asked to verify that the BIM models have been modified according to the new granularity of the construction schedule.

This process should be formalised in a contractual document, such as the PGC (site management plan, in French Plan de Gestion de Chantier), under the responsibility of the project manager.

4.4. Phase 4: To Supervise BIM Models Production for 4D BIM Use Case

As noted earlier, it is common for French project stakeholders to partially achieve only certain BIM use cases initially required by the client. This is partly due to the BIM maturity and expertise of some project stakeholders and partly due to the disparity between the required and available LoDs. A further important factor is the way the BEP is elaborated. For the use of 4D BIM, it often consists of a brief and summary description contained in a section that is less than one page in length. The proposals below aim to optimise the content of the BEP to better elaborate and specify the implementation of 4D BIM.

Step 1: To explicitly mention the obligation to achieve 4D use and above all what its purposes are. Thanks to the work carried out in Phase 1, 4D applications are easily understood using the SMART objectives identified.

Step 2: To detail which actor must perform or contribute to which task(s) in order to achieve the 4D BIM use objectives. To do so, the RACI matrix (Responsible, Accountable, Consulted, Informed) was proposed. This project management tool [99] is usually used for classifying project stakeholders through a 'responsibility assignment matrix', thus developing a grid specifying who does what in the project. Here it was adapted by the authors for specifying the scheduling process (Figure 4) and the BIM model production (Figure 5) to facilitate the use of 4D BIM.

Step 3: To indicate in the general process describing the BIM model's production when the tasks related to the 4D BIM use case must be performed. This must be undertaken before the BIM models are checked and coordinated so that the BIM manager can control deliverables produced for executing the 4D BIM use case and verify the presence of the parameters that will serve to link the BIM models to the schedule.

Step 4: The process of 4D BIM implementation needs to be very detailed to indicate to the project actors the method adopted. It should begin with a reminder of the SMART objectives envisioned; the modelling rules to comply with the rationale for model structuring and breakdown; the parameters to be created and information on who provides them and when; information on when and how the work will be controlled; the criteria for choosing 4D BIM software; and information on who links the model to the schedule to produce the expected deliverables, and when this will occur.

Clarifying and detailing the process and procedure for implementing a BIM use case, whether it is 4D-BIM-related or not, allows project stakeholders to have a good understanding and clear idea of the tasks to be performed. The more the production and control process is explained, the more the probability of reaching the project objectives increases.
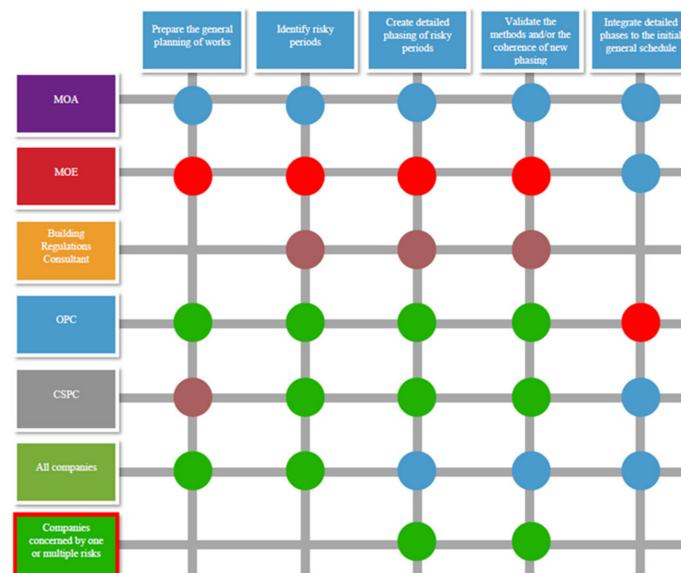
Figure 4. RACI matrix for implementing the scheduling process when using 4D BIM.
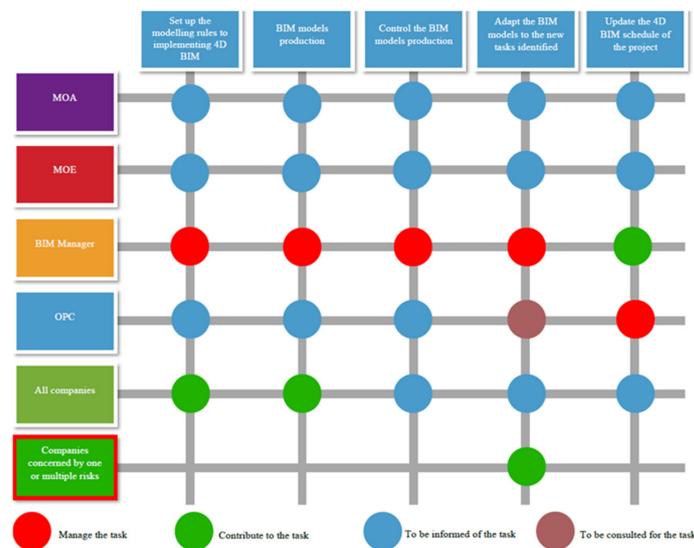
Figure 5. RACI matrix for BIM model production when using 4D BIM.

5. Case Study of the Nanterre 2 CESI Project

This first case study extends the 4D BIM literature by presenting empirical evidence on the implementation and use of 4D BIM tools during the construction phase of an educational building. The Nanterre 2 CESI project (Figure 6) is a four-storey building intended to increase the teaching capacity of the CESI campus in Nanterre. There were two reasons for adopting BIM for the design and delivery of the project. Firstly, so that the deliverables produced by the project participants could be saved at each phase in order to make them available to CESI teaching teams and serve as real case studies. Secondly, so that the information contained in the deliverables allowed CESI to manage the operation and maintenance of the building using BIM-based workflows.
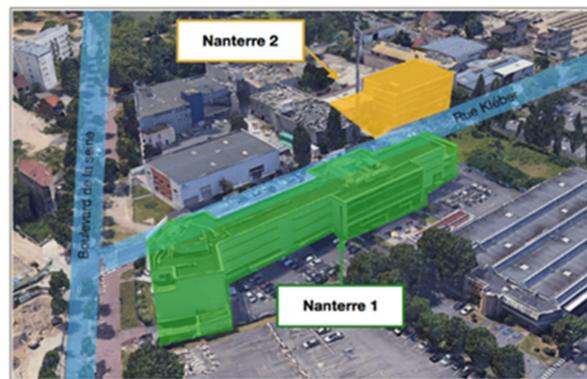
Figure 6. Location of Nanterre 2 (new) and Nanterre 1 (existing) buildings on Rue Kléber.

5.1. Nanterre 2 CESI Project

The Nanterre 2 CESI project is composed of: (i) a ground floor of 800 m^2: coworking and catering space; (ii) the first floor to the third floor (800 m^2 per floor): teaching spaces; (iii) the fourth floor (600 m^2): Living Lab. (i.e., BIM modelling, RA/RV, and digital simulation spaces); (iv) parking for employees, professors and/or researchers, and green spaces. Construction works were planned for a 12-month period (between 5th May 2018, and 31st May 2019). CESI, as client, specified the use of BIM for the design and construction of the Nanterre 2 building. Apart from its intrinsic commitment to the use of the latest available technologies, CESI also wanted to use the project as a case study that provided data for teaching and research programmes in digital construction. Therefore, in commissioning the Nanterre 2 building, the client, CESI, followed a similar process to that

described in (the later published) ISO 19650: 2 [81]. This involves the 'appointing party' specifying, as part of its tender documents, a set of 'exchange information requirements' (EIRs) which prospective appointees then reflect in their tenders, and which form the basis (subject to pre-contract negotiation) of the appointed delivery team's BEP. In this case, a BIM specification document (equivalent to a set of EIRs [81]) was produced that included 10 BIM use cases. These were:

- Site modelling;
- Project communication;
- Project review;
- Analytical studies *;
- 4D BIM*;
- 5D BIM* (an application integrating the model with cost management activities);
- Management of design conflicts and clashes;
- Logistics support *;
- Regulatory compliance checking;
- Management of construction works and equipment *

Ultimately, however, for the works to proceed, it was agreed that the appointed delivery team could omit several (marked as *, above) of the BIM use cases. The main reasons for this were the deficiency of certain aspects of the requirement specifications as well as the diversity in the level of BIM expertise and maturity within the delivery team. One such omission was the requirement to provide 4D BIM. For this use case in particular, the BIM specification document only stated that a 4D software must be mastered, indicating Navisworks as an example. The mistake made was to only cite the type of software without specifying its capabilities. In this case, Navisworks was not capable of managing the construction site and monitoring, in real time, construction work progress. These were precisely the two uses of 4D BIM expected by CESI. The second shortcoming was due to the procedure described. It was simply indicated that a 3D model and a schedule must be linked to enable the extraction of a video animation and the phasing logbook (in French the carnet de phasage). This procedure was based on the Hardin and McCool method [96]. It was not indicated which 4D parameters should be produced, by whom, and how to ensure overall planning consistency. This being the case, and believing that it had sufficient in-house expertise, CESI decided to implement the 4D BIM planning of Nanterre 2 internally with the help of academic research teams that were familiar with digital construction. Their experience in doing so is the basis of the developmental case study reported here.

5.2. Application and Illustration

The application of the proposed 4D planning method is structured in four phases as follows:

5.2.1. Phase 1: To Express the 4D Objectives in an Initial BIM Specification Document

Table 1 proposes a reformulation of the 4D requirements so that they can be understood without ambiguity and therefore allow the project teams to propose relevant solutions to answer them.

Table 1. Phase 1: Expression of 4D objectives in the BIM specification document.

N°	Initial Formulation	SMART Formulation
1	The BIM model must include data related to equipment and temporary structures required for onsite construction works.	The use of 4D BIM must enable visualisation and analysis of space occupation by equipment and temporary structures when two companies work within the same area.
2	The update of the schedule must be conducted in real time and correspond to the exact progress of onsite construction works.	At any time during the construction phase, 4D BIM planning must enable the measuring of construction work progress within +/−3 days.

5.2.2. Phase 2: To Identify Information Requirements and Relevant Workflows

Step 2 (*here Step 1 is not necessary*): To determine the information to be produced for each 4D objective (Table 2), the BIM manager must understand how 4D BIM tools work. The more this BIM actor is aware of the latest technological advances, the more technically and economically viable its 4D planning strategy is. Thus, a review of existing 4D BIM tools may be necessary if this use case is not usually implemented by the BIM manager.

Table 2. 4D information requirements related to the 4D BIM use case.

4D BIM Objectives	Information to Be Produced
The use of 4D BIM must enable visualisation and analysis of space occupations by equipment and temporary structures when two companies work within the same area.	- Dates and durations of the co-contracting periods - Names of the companies concerned - Nature of the work - Locations of occupied areas - Dimensions and footprints of equipment/temporary structures - Equipment circulation areas - Equipment type
At any time during the construction phase, 4D BIM planning must enable the measuring of construction work progress within +/- 3 days.	- 4D parameters linked to the schedule - Project task flowchart level - Nature of the links between the tasks

Step 3: BIM modelling and collaboration platforms were imposed. A workflow was established based on these tool constraints. However, no 4D planning tool nor project participant with expertise in using this tool was involved in the project. Therefore, the following two assumptions were made:

Hypothesis 1. 'The BIM manager masters the 4D planning tool. If necessary, he can be called upon to resolve the technical problems encountered.'

Hypothesis 2. 'As soon as the phase is launched, under the responsibility of the BIM manager, the project OPC is introduced to BIM and sufficiently trained to master the 4D planning tool.'

As for the Nanterre 2 project, Hypothesis 2 was relevant, since the BIM manager had had expertise with regard to using Synchro Pro in previous projects. Therefore, the workflow proposed and implemented is illustrated in Figure 7.

N°	Deliverable	Tools	Approving entity	Dissemination methods
1	Planning	Excel / Project	OPC	EDM* SharePoint
2	Schedules compilation	Project	MOE	EDM SharePoint
3	BIM models	AUTODESK REVIT	BIM Manager	EDM SharePoint
4	4D planning	SYNCHRO	MOE	EDM SharePoint

*Electronic Document Management

Figure 7. Tools and methods for producing 4D BIM deliverables.

5.2.3. Phase 3: To Design a Project Schedule Adapted to the Use of 4D BIM

The process represented in Figure 8 can be attached to the project's BEP in order to guide stakeholders in designing and developing schedules that are suitable for the 4D BIM

use case. The following steps should enable the BIM manager to transform the traditional project planning process by taking into account the 4D BIM objectives.
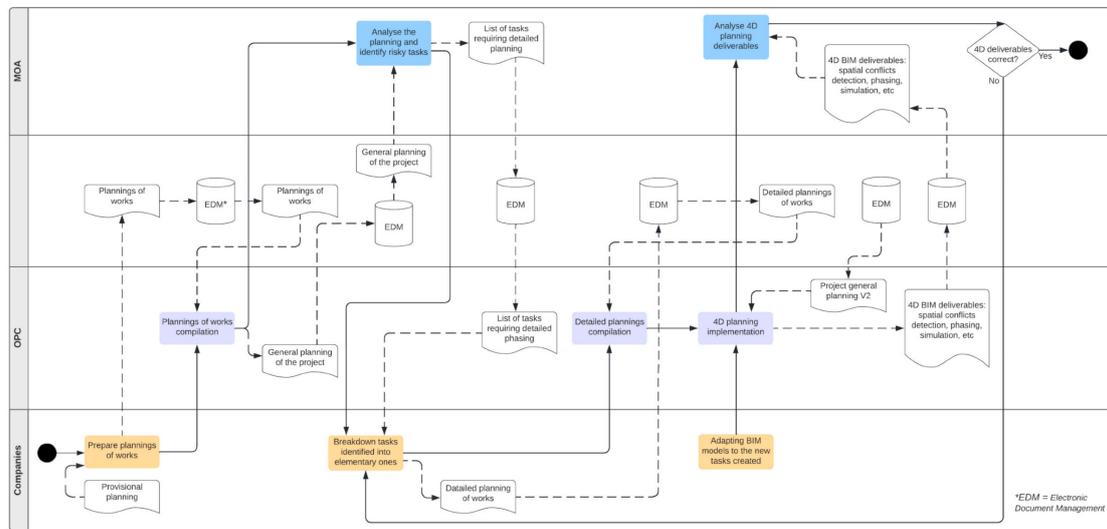
Figure 8. Summary of Phase 2's process - Design of the project schedule adapted for the use of 4D BIM.

Step 1: The traditional schedule is used as an input. This document is produced by the project OPC through combining and including all business planning of the project. The project tasks flowchart is of level 3 (Figure 9).
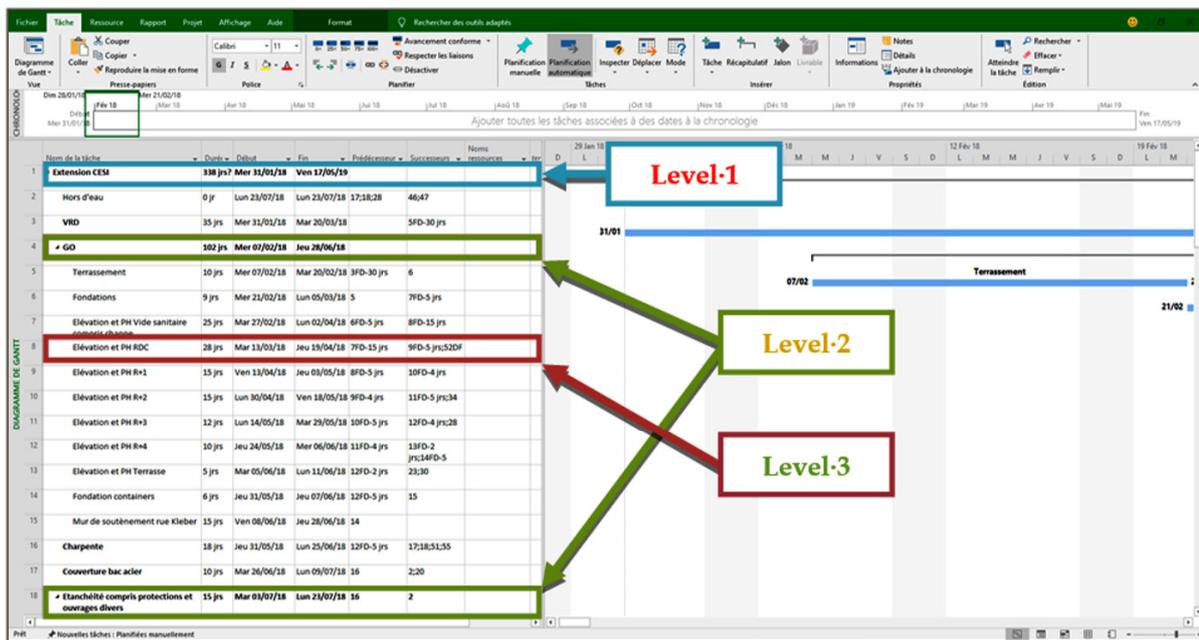
Figure 9. Screenshot of Nanterre 2 CESI project schedule.

Step 2: The first objective that must be studied is the identification of periods that could represent a certain risk and for which 4D planning can provide an added value in terms of safety and space optimisation. The previously identified actors must analyse the sequencing of the tasks of the initial planning and list each of its periods in order to study them in detail.

Step 3: The second objective is to produce the information listed by the BIM manager in Phase 2. Collaboration between project stakeholders should enable the production of

precise information and allow for the performance of a first optimisation for the initial planning. Thereafter, 4D planning will enable the optimisation and the validation of the planning generated. At this stage, all of the 4D parameters related to the analysis of occupied spaces (4D BIM Objective N° #1) are known. As for the 4D objective linked to monitoring construction work progress, it is up to the OPC, possibly with the support of the BIM manager, to choose their own method. For the Nanterre 2 project, the initial schedule already included the links between the tasks. It therefore remains to determine the 4D parameter to be created so as to link the schedule to the BIM models, and to increase the level of the project tasks flowchart in order to optimise the precision of the progress monitoring process. Since the BIM model was created using Autodesk Revit software, a simple and straightforward solution is to create a text parameter and name it '*BIM_WBS*'. This parameter is created and assigned to all the BIM model objects. Then, the exact name of the planning task to which it must be linked needs to be entered. By doing so, it was possible to automatically assign all the objects of the BIM model to the project schedule. Table 3 summarises the information produced.

Table 3. Summary of the information produced at Step 3 of Phase 3.

4D BIM Objectives	Information to be Produced	Information Identification or Its Location
The use of 4D BIM must enable visualisation and analysis of space occupations by equipment and temporary structures when two companies work within the same area	Dates and duration of co-contracting periods	Planning
	Name of the companies concerned	Planning
	Nature of the work	Planning
	Location of occupied areas	Planning
	Dimensions and dimensions of equipment/temporary structures	Planning
	Equipment circulation areas	Planning
	Equipment type	Planning
At any time during the construction phase, 4D BIM planning must enable the measuring of construction work progress within +/- 3 days.	4D parameter linked to the schedule	'BIM_WBS': Planning
	Project task flowchart level	Planning
	Nature of the links between the tasks	Planning

Step 4: Phase 3 ends when all the information produced is gathered and combined. Using the initial schedule, the OPC transforms all tasks by integrating 4D information, and then shares the resulting schedule with the MOE for approval (Figure 10).
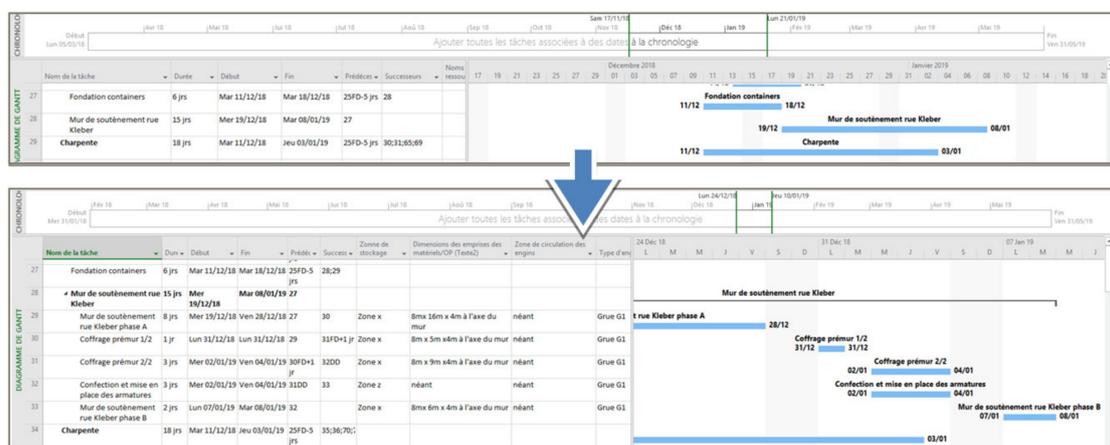
Figure 10. Evolution from initial planning to final planning (screenshot from Microsoft Project).

5.2.4. Phase 4: To Supervise BIM Models Production for 4D BIM Use Case

This phase allows the project contractors to integrate 4D BIM information into their BIM models to achieve the 4D BIM objectives of the project. By relying on the project BEP, construction companies must be able to use the information provided in the schedule resulting from phase 3.

Step 1: The BIM manager must indicate in the BEP the main BIM objectives of the project. At this stage, the project BIM contributors should be informed that a 4D planning process will be implemented. The BEP section following the general objectives must indicate in detail and in a SMART way, what the objectives of each BIM use case are, and in particular, the objectives related to 4D BIM.

Step 2: This step consists of precisely determining the degree of responsibility and involvement of each project participant towards the achievement of the 4D BIM objectives. Therefore, it was necessary to use the RACI matrix templates proposed in Figures 4 and 5 and substitute the actor names by the actual companies that will execute the project.

Step 3: The two production processes given in Figures 8 and 9 were integrated into the project BEP to explain to the BIM contributors how the 4D BIM use case should be implemented.

Step 4: Once the objectives have been identified and the production methods thoroughly detailed through Steps 1, 2 and 3 of the current Phase 4, the workflow to be implemented was clearly explained to enable efficient project communication and information exchange.

5.3. 4D BIM Planning Implementation

In this section, the 4D planning of structural works of the Nanterre 2 CESI project is performed. The initial planning is first linked to the digital model without taking into account the 4D BIM objectives of the project. Then, the proposed method is applied to integrate the information produced in the previous subsections.

5.3.1. Primary 4D BIM Planning

First, the 4D parameter 'BIM_WBS' is created and integrated into the BIM model of structural works. Then, the BIM model is exported from the authoring platform using the Synchro Plug-in. The project schedule is also imported and the links between the tasks are preserved. Finally, the objects of the BIM model are assigned to the corresponding tasks. This first summary 4D BIM schedule, which can be exported in video format (.AVI) or in phasing form (.JPEG), allows project teams to check that the project workflow is correct. It is now possible to work directly on the 4D planning software to make changes to the project schedule. However, the BIM objectives of the project have not been achieved yet.

5.3.2. 4D BIM Planning According to the CESI Method

To test and validate the proposed method, it should be confronted with realistic co-contracting issues. To do so, the primary 4D planning performed in the previous subsection was used along with a detailed scenario including periods where four tasks overlap, and three companies 'coexist' on the construction site. The 4D parameters to be produced to meet the 4D BIM requirements of the Nanterre 2 project have been identified in Section 4.2. The OPC integrates this information into their planning (see process in Figure 8) while companies make the necessary changes to fill in the information in the BIM models (see process in Figure 11). The compilation of these two deliverables makes it possible to create a more detailed 4D plan which was used to validate and/or optimise constructive choices. Figure 12 illustrates the result of 4D BIM planning. By creating the spaces linked to each activity, an analysis of the workflow can be performed to detect hazard sources and reduce their impact. In this planning scenario, it has been detected that the work areas on the ground floor overlap during HVAC and ELEC interventions. Preventive actions can therefore be taken to manage the space where these two activities are located so that no hazards due to this co-contracting slow down the work progress.
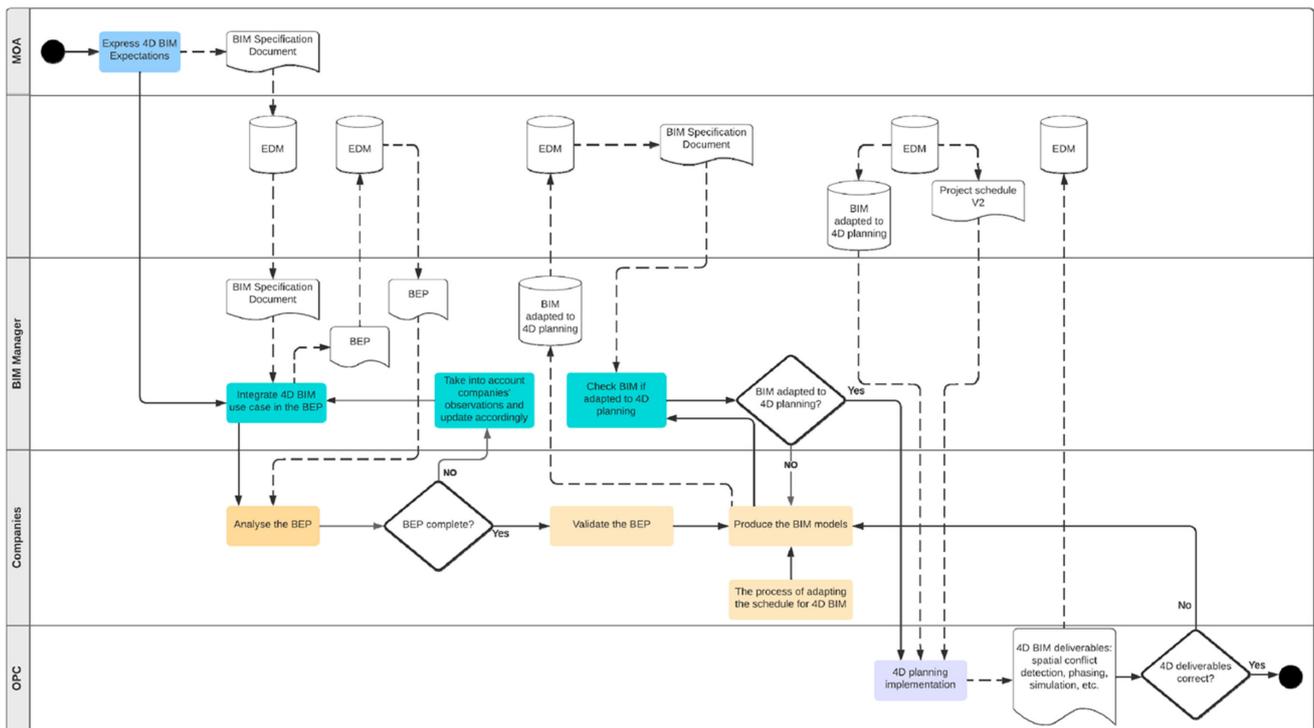
Figure 11. Summary of the Phase 3 process - Supervision of BIM model production for 4D BIM use case.

Figure 12. 4D BIM planning of the Nanterre 2 CESI project using the CESI method.

The 4D BIM planning performed using the proposed method enables the achievement of the client's objectives better than the primary 4D planning. Indeed, the use of 4D information, identified from the second phase of this method, allowed the actors to focus effectively on the expectations of the MOA (namely, the evaluation of the result of 4D BIM planning with regard to the 4D objectives) as shown in Table 4.

Table 4. Proposed method evaluation regarding the client's 4D BIM objectives achievement.

4D BIM Objectives	Evaluation
The use of 4D BIM must enable visualisation and analysis of space occupations by equipment and temporary structures when two companies work within the same area	- The zones have been identified and taken into account for the planning of the works. - An analysis of the zone interfaces was performed, which made it possible to detect an overuse of certain spaces. - The equipment circulation zone has been taken into account by means of '3D paths' linked to the tasks.
At any time during the construction phase, 4D BIM planning must enable the measuring of construction work progress within +/−3 days	As shown in Figure 12, the new 4D planning required the creation of new sub-tasks and therefore the increasing of the level of the project tasks flowchart. This makes it possible to specify the exact nature of the work to be carried out and therefore to assess more precisely its progress.

6. Automating 4D BIM Planning: The RINNO Case Study

Research leveraging the use of 4D BIM data using AI tools is lacking [13] although such an integration is crucial to optimise and develop more effective strategies for construction project planning through the development of automated tools to, for example, automatically generate and simulate different scenarios [40]. Furthermore, there is a dearth of methods and tools dedicated to renovation project management. New construction projects have usually been prioritised in terms of design, planning and management tool development. When possible, these tools are adapted to the context of renovation projects [100] which represents one of the main factors that make their performance typically lower than that for new constructions [101,102]. The research study reported in this section is part of the RINNO research project [103,104] which aims to develop a holistic multi-disciplinary platform that will ensure the acceleration of the rate of deep renovation in EU residential buildings. Here, an ontology is introduced, and its application is illustrated within the context of building renovation. Ontologies are useful AI tools in formalising specific domain knowledge, including their concepts, relations, and constraints [41]. They enable process automation and tool development as they provide a machine-readable representation of knowledge.

6.1. Renovation 4D Planning Ontology

Figure 13 presents the ontology developed within the RINNO project [103,104] dedicated to generating 4D BIM schedules for renovation projects. The overview given in Figure 13 is a UML (Unified Modelling Language) class diagram illustrating the ontological concepts, their relations and constraints, as well as the attributes or properties that define each concept (here class or entity) to facilitate its implementation as a renovation knowledge base in the case of this study.

As presented in Figure 13, a 'Built Asset' is composed of several 'Building Elements' (e.g., windows, walls) and WBSs (Work Breakdown Structures, e.g., floors, external façades) where each 'Building Element' belongs to a WBS. A 'Building Element' requires one or many 'Renovation Activity' components to be renovated, and this may be carried out by installing one or many 'Innovative Products' (e.g., photovoltaic panels, solar collectors). Each 'Renovation Activity' is temporally constrained by activities that should start and finish before it, whereas some others will be triggered and executed after its completion. It also requires a set of 'Material', 'Workforce', and 'Equipment' so it can be executed and may cause 'Disruption' to the building occupants. The 'Disruption' concept is beyond the scope of this paper and will be detailed in future research, since its estimation and simulation is one of the RINNO project targets.

The ontology proposed was populated into a database using the SQL Server. This database included several tables, and each one enabled the implementation of a concept from the ontology. The tables describe in detail data related to renovation activities, their

sequencing rules, constraints, duration, cost, equipment, etc., all gathered, structured, and verified with the help of the RINNO project partners.
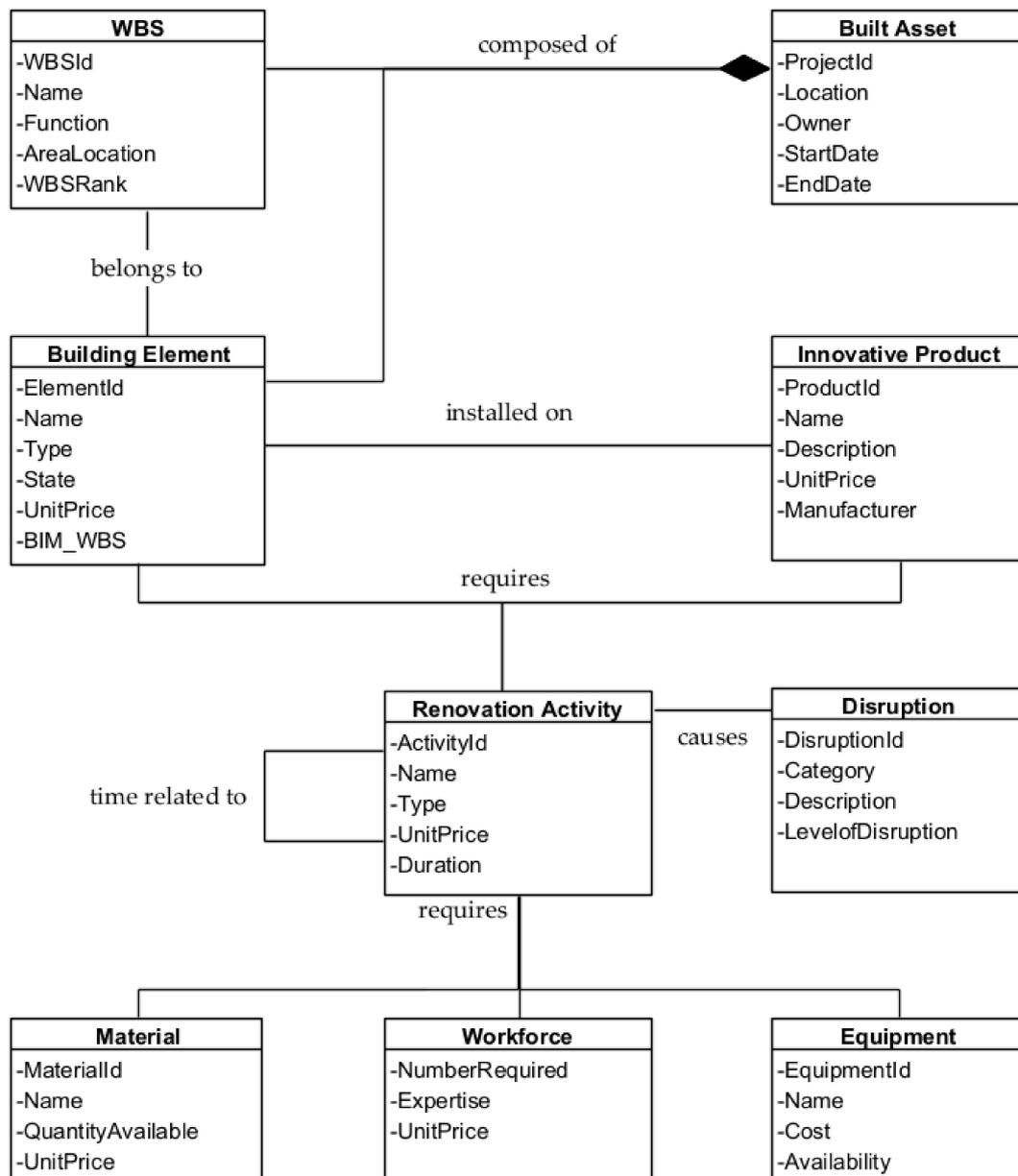
Figure 13. Renovation 4D planning ontology—UML class diagram.

6.2. Automated 4D BIM Planning and Simulation Process

Figure 14 presents the system architecture of the digital tool developed and Figure 15 the automated 4D BIM planning process implemented; both are based on the ontology introduced in the previous subsection. The automated process, represented here as a UML scenario diagram, enables the BIM manager to leverage the BIM data and automatically generate and simulate the 4D BIM planning based on a renovation scenario identified at the beginning of the process. Indeed, after checking the BIM model and selecting a renovation scenario via two main GUIs (Graphical User Interfaces) (Figure 16C,D), the 'RINNO Renovation Engine' component coordinates the 4D BIM planning process by: (i) updating the BIM model if necessary to integrate project-related information (Figure 16A); (ii) generating traditional (Gantt) planning using (a) the scenario selected by the BIM manager in order to identify WBS, renovation activities to be performed, and equipment used, (b) the BIM

model to extract BIM elements considered by the scenario simulated and corresponding quantity take-off (QTO), and (c) the ontology to map activities to WBS and BIM elements and assign relevant equipment to activities and estimate their durations; (iii) updating the BIM model using the traditional planning generated, particularly by integrating the activities data and initialising the 'WBS_BIM' parameter; and (iv) simulating the 4D BIM planning created through the BIM management tool.
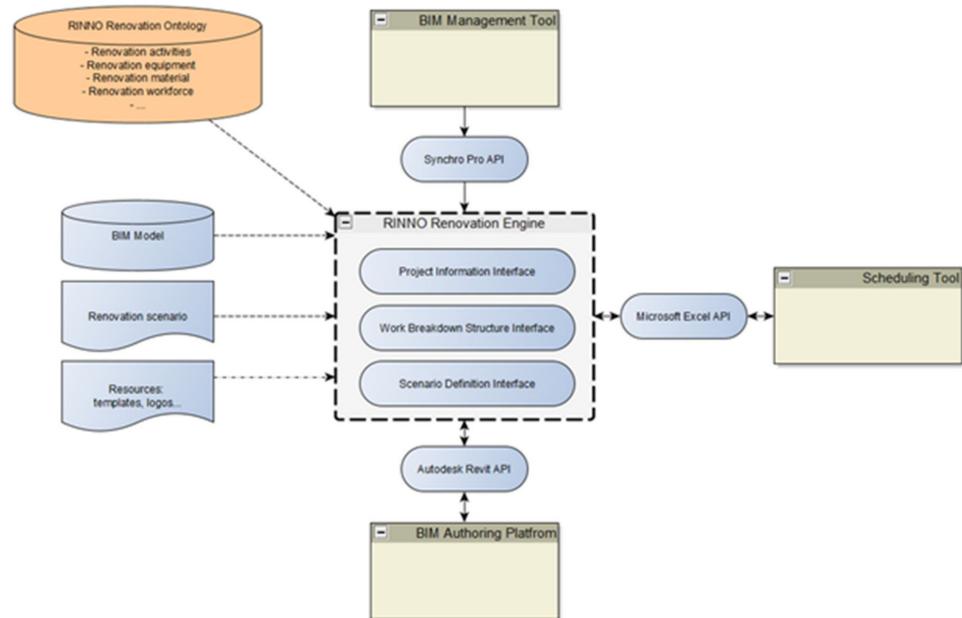
Figure 14. System architecture of the 4D BIM digital tool.
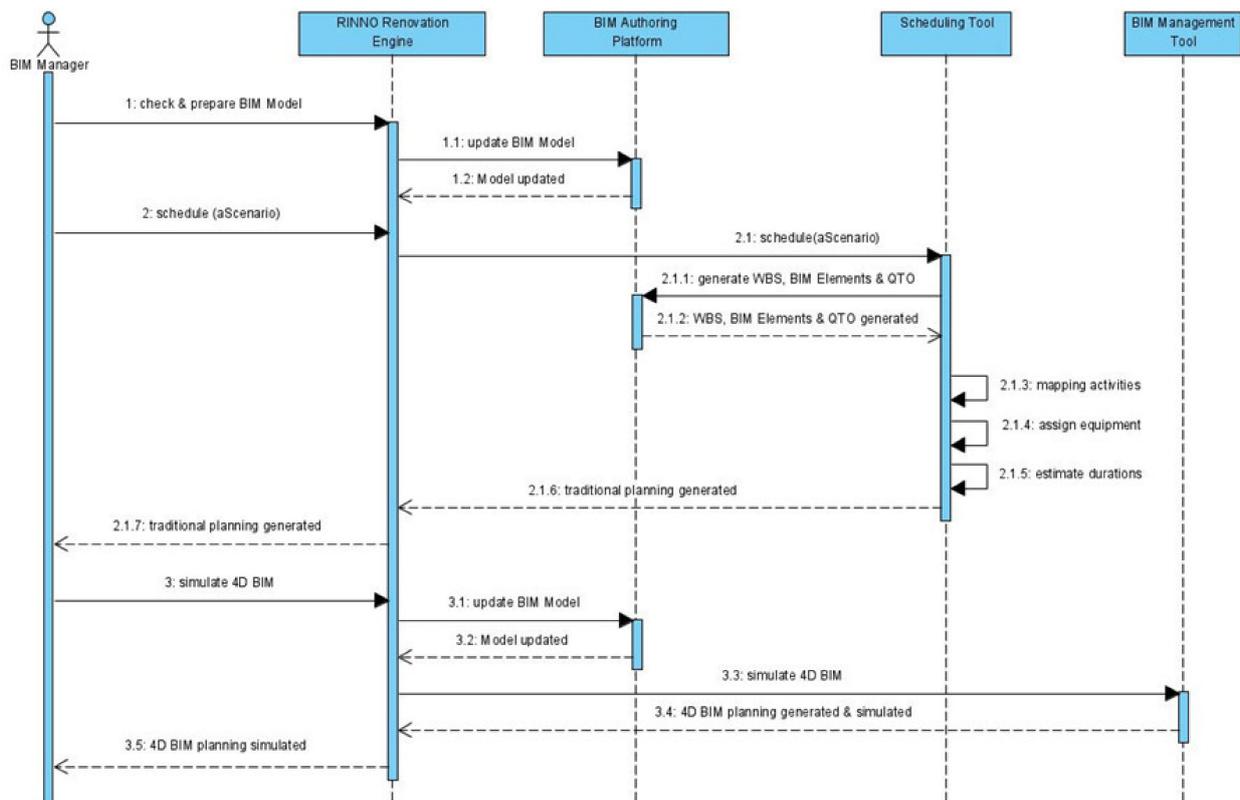
Figure 15. Automated 4D BIM planning and simulation.

(**A**)

(**B**)

Figure 16. *Cont.*

(**C**)

(**D**)

Figure 16. RINNO Renovation Engine GUI. (**A**) Project details interface. (**B**) WBS interface. (**C**) Scenario interface 1 for renovation activities selection. (**D**) Scenario interface 2 for renovation equipment selection.

Figure 16 illustrates the GUI of the RINNO Renovation Engine developed to: (i) facilitate interaction with the tool; (ii) automate and assist users for renovation scenario definition and generation; and (iii) streamline the whole automated 4D planning and simulation process.

7. Discussion, Conclusions, and Perspectives

This work was an opportunity to study project management in general, and then to look at the new methods that have emerged with recent technological advances. Traditional planning methods are often ineffective in taking into account all the uncertainties and hazards that may occur during a construction project. As a result, time and cost targets are rarely met. BIM represents an evolution of these practices and can be a useful way to optimise planning methods. Numerous studies show that 4D BIM helps to reduce planning errors, promotes collaboration between stakeholders, and helps project teams make effective decisions.

7.1. The Nanterre 2 CESI Project Case Study

The first case study showed that not all actors can afford to innovate and adopt BIM for project management. Although the use of 4D BIM was specified and required by the client, it was not implemented in the Nanterre 2 CESI project, mainly due to a lack of practical and simple methods of implementation, as well as the low and heterogeneous level of BIM training and expertise of the project actors.

To contribute to the democratisation of the 4D BIM use case, a structured and practical method was proposed. This method was based on a four-step process to enable project participants to (i) clearly and in a SMART way, express the 4D BIM objectives from the beginning of the project in the BIM specification document, (ii) identify information requirements and relevant workflows to achieve these objectives, (iii) design an adapted 4D BIM plan, and (iv) supervise the BIM model's production to enable the implementation of the 4D BIM use case. The proposed method promotes collaboration between project actors and guides them towards information production and management. Pragmatic and detailed processes and methods were introduced and applied on the Nanterre 2 CESI project to implement the 4D BIM use case and related objectives required by the client. This implementation enabled the illustration of some of the advantages 4D BIM can bring to a construction project. The effective adoption and development of 4D BIM can provide efficient tools for monitoring work progress and so represents a significant added value to ensure that time and cost constraints, when initially planned, are constantly satisfied. Sacks et al. [105] proposed a matrix that contains 56 interactions between Lean methodology principles and BIM functionalities to clarify possible synergies between the two methodologies. Using this matrix as a starting point to develop the proposed method would have enabled more pragmatism and better streamlined and optimised processes alongside the workflows proposed in this paper.

Furthermore, it should be noted that objective N° #2 (i.e., 'At any time during the construction phase, 4D BIM planning must enable measuring construction works progress within +/- 3 days') was difficult to achieve. This objective should be studied in detail so as to clearly understand what the actual intention of the client was. Objectively, 4D BIM provides very little added value for monitoring the work progress when data are not collected in time and the BIM models are not updated regularly. Indeed, the accuracy of the work progress depends on the frequency with which the OPC carries out their onsite supervision and monitoring missions. In general, clients have little knowledge of the possibilities and limits of digital tools. It would be very difficult to visualise the 'exact' onsite work progress as it would require a BIM model containing each element, equipment, or work structure installed and used, temporary or permanently, during each construction phase. Therefore, the assistance of an AMO BIM to help the client express and formalise their requirements in a SMART manner is crucial. Furthermore, IoT and autonomous systems [106] can play a fundamental role in collecting onsite data efficiently and regularly so to enable the automatic and regular updating of BIM data.

Moreover, the proposed method, if it were to be implemented in more typical circumstances, would require certain levels of collaboration between key project actors. The two RACI matrices (Figures 4 and 5) show the required interactions between key project actors for the effective integration of the two processes (construction schedule and BIM model creation). The collaboration of these key project actors is crucial. The issue of collaboration is frequently raised when the realisation of the benefits of BIM are considered. Increased collaboration is not only a prospective beneficial outcome of BIM adoption [107]; it is a prerequisite for the full attainment of these potential benefits [108]. Thus, studies have suggested that the realisation of BIM's key benefits relies upon the degree of collaboration achieved and that this is not achievable with traditional project procurement approaches [109–111]. Objectively, the adoption of 4D BIM provides very little added value without the necessary and timely integration of construction scheduling and BIM model creation; a process that is difficult to achieve in traditional project frameworks.

The Nanterre 2 CESI building has been open to students since September 2019. The operation and maintenance management of this building is expected to be implemented using BIM technology. To undertake this, it is essential to implement and use a classification system such as Uniclass 2015. Based on a set of consistent and hierarchically organised tables, Uniclass 2015 allows the classification of all types of elements that could be considered in the context of a construction project, from the most complex items such as industrial or residential complexes, to the most detailed items such as door locks or the covering and finishing of products. This system also allows for the classification of physical objects using the 'Entities', 'Elements', 'Systems' and 'Products' tables, as well as construction processes and activities through the 'Activities' table. Consequently, it allows for the simultaneous integration of PBS (Product Breakdown Structure) and WBS [51] and therefore the implementation of BIM for the operation phase in which the building objects are linked to their respective operation and maintenance activities. This ontological link between objects and activities should also enable the standardisation and automation of 4D BIM planning and simulation for both construction and operation phases.

7.2. The RINNO Project Case Study

This paper also introduced an ontology that is dedicated to 4D BIM planning within the context of renovation projects and demonstrated its applicability and value by designing and developing the RINNO Renovation Engine to enable automatic 4D planning generation and simulation. Ontologies are known to be powerful AI tools that allow the formalization of specific domain knowledge by providing it in a machine-readable format. To allow users to test and simulate different 4D planning strategies, the automated 4D planning process proposed enables 4D scenario identification and generation in a simple, interactive, and automatic way through a set of user-friendly interfaces. In the literature, ontologies are usually implemented using the Protégé platform [112]. Based on expert's input and knowledge from renovation engineering documents, Amorocho et al. [99] developed an ontology restricted to the installation of common renovation products, such as windows, HVAC components, and external thermal insulation panels. The 4D BIM ontology proposed in this paper considers the general case of renovation projects and so includes all related activities: innovative products installation as well as general activities, such as 'façade insulation with cavity insufflation'. Furthermore, to improve interoperability and interfacing between the BIM authoring tool (Autodesk Revit), the BIM management tool (Synchro Pro), and the scheduling tool (MS Excel), the RINNO Renovation Engine was developed as a plugin using the C# programming language, and the ontology was implemented as a knowledge base and populated using both the SQL Server tool and the RINNO partners' expertise and knowledge. However, further research is needed in order to extend and validate the content of the domain expert knowledge in terms of renovation activities, equipment, innovative products, sequencing rules and constraints between activities, costs, etc. For that, a survey has already been launched across many EU countries, and the results will be soon reported. Since costs data will be validated by the survey, it can be then integrated to

implement a 5D BIM use case, thus enabling the economic assessment and monitoring of renovation projects.

Disruption was one of the concepts represented through the UML class diagram of the 4D BIM planning ontology; however, it was not further developed nor detailed. This concept usually refers to a disturbance which interrupts, diminishes, or alters the usual functioning of an activity, service, or system, and its impacts on the overall efficiency and productivity of the project [113]. Disruptions and delays are two interrelated concepts. While disruptions can cause delays in the progress of construction works, delays similarly can generate disruptions and a loss of productivity. Although renovation may be disruptive per definition, project participants should ensure the managing and minimisation of the impact on occupants. To build trust and minimise this impact, communicating with residents and explaining the renovation process in advance can play a crucial role [114]. Certainly, BIM-based disruption simulations, along with detailed 4D BIM planning for retrofitting works, can help address this need, which is one of the RINNO project targets that will be presented in future.

Ultimately, to validate and evaluate its impact, the automated 4D BIM planning tool (i.e., the RINNO Renovation Engine) should be tested and applied using real case studies. For this, the RINNO project and its partners offer four demonstration sites in France, Denmark, Greece, and Poland, respectively (Figure 17) with a total floor area of 3 386 m2 including both single-family and multi-family residential dwellings. These buildings reside in different climatic regions, and comply with diverse building codes and regulations, having been built using very different construction components and tools, and they are equipped with different construction systems and other building amenities. Previous research [115] recommended simplifying the 4D BIM model to ensure it does not contain too many unnecessary details and that it enables the clear visualisation of retrofitting works. For the design and planning phase, other research [116,117] specified that LoD 200 should be adopted. These hypotheses, along with the BIM model with granularity relevant to 4D simulations, will be thoroughly studied while demonstrating the 4D automated process using the RINNO's demo sites.
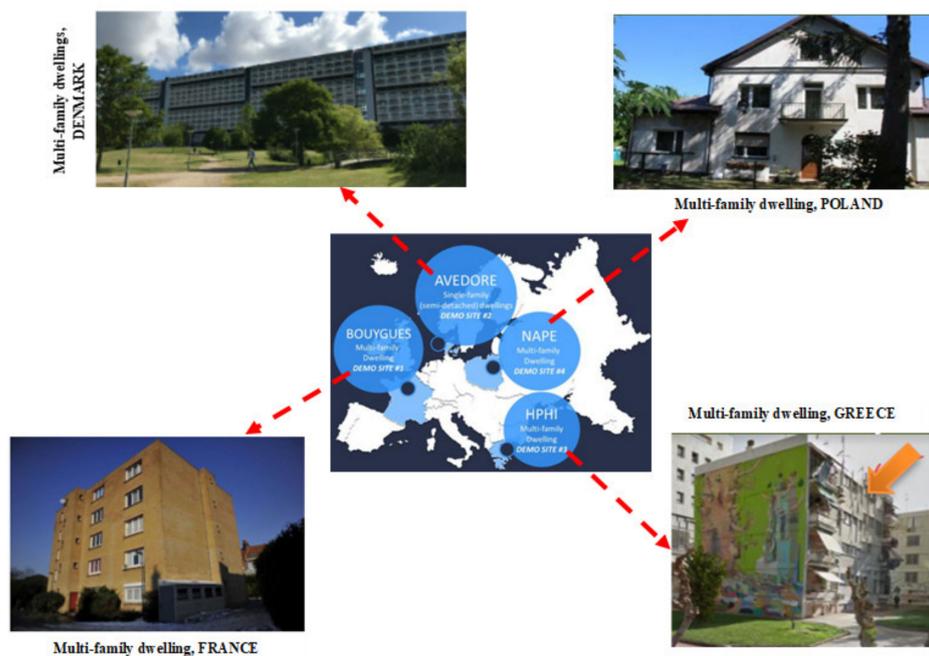
Figure 17. RINNO Demo Sites.

Appendix A

Table A1. French terminology for project actors with English equivalents.

French Role	Abbreviation	English Equivalent
Maitre d'ouvrage	MOA	Client, Employer, Owner
Maitre d'œuvre	MOE	[varies] Client's Representative, Project Manager, Architect, Engineer
Assistant à la maitrise d'ouvrage	AMO	On-site assistant to the above
Ordonnancement, planning, coordination	OPC	Consultant planning specialist [unusual in UK context]
Coordinateur santé et protection de la sécurité	CSPS	Health and Safety consultant. Planning supervisor.
Assistant à la maitrise d'ouvrage BIM	AMO (BIM)	BIM Manager

References

1. Cavka, H.B.; Staub-French, S.; Poirier, E.A. Developing Owner Information Requirements for BIM-Enabled Project Delivery and Asset Management. *Autom. Constr.* **2017**, *83*, 169–183. [CrossRef]
2. Buisman, A. *How Are Engineering and Construction Companies Adapting Digital to Their Businesses*; Ernst&Young: London, UK, 2018.
3. Camacho, A.; Cañizares, P.C.; Estévez, S.; Núñez, M. A Tool-Supported Framework for Work Planning on Construction Sites Based on Constraint Programming. *Autom. Constr.* **2018**, *86*, 190–198. [CrossRef]
4. Conlin, J.; Retik, A. The Applicability of Project Management Software and Advanced IT Techniques in Construction Delays Mitigation. *Int. J. Proj. Manag.* **1997**, *15*, 107–120. [CrossRef]
5. Importance of Scheduling in Construction Projects. Available online: https://theconstructor.org/construction/const-management/importance-scheduling-construction-projects/1710/ (accessed on 22 April 2022).
6. Egwim, C.N.; Alaka, H.; Toriola-Coker, L.O.; Balogun, H.; Sunmola, F. Applied Artificial Intelligence for Predicting Construction Projects Delay. *Mach. Learn. Appl.* **2021**, *6*, 100166. [CrossRef]
7. Chen, G.-X.; Shan, M.; Chan, A.P.C.; Liu, X.; Zhao, Y.-Q. Investigating the Causes of Delay in Grain Bin Construction Projects: The Case of China. *Int. J. Constr. Manag.* **2019**, *19*, 1–14. [CrossRef]
8. Aravindhan, C.; Santhoshkumar, R.; Bonny, K.; Vidhya, K.; Manishankar, S.; Dhamodharam, P. Delay Analysis in Construction Project Using Primavera & SPSS. *Mater. Today Proc.* **2021**, *7*, 186. [CrossRef]
9. Robinson, T.G. *Global Construction Market to Grow $8 Trillion by 2030: Driven by China, US and India*; Global Construction Perspectives and Oxford Economics: London, UK, 2015; p. 44.
10. Flyvbjerg, B. What You Should Know about Megaprojects and Why: An Overview. *Proj. Manag. J.* **2014**, *45*, 6–19. [CrossRef]
11. Chen, S.-M.; Chen, P.-H.; Chang, L.-M. Simulation and Analytical Techniques for Construction Resource Planning and Scheduling. *Autom. Constr.* **2012**, *21*, 99–113. [CrossRef]
12. Yogesh, G.; Hanumanth Rao, C. A Study on Linear Scheduling Methods in Road Construction Projects. *Mater. Today Proc.* **2021**, *47*, 5475–5478. [CrossRef]

13. Gondia, A.; Siam, A.; El-Dakhakhni, W.; Nassar, A.H. Machine Learning Algorithms for Construction Projects Delay Risk Prediction. *J. Constr. Eng. Manag.* **2020**, *146*, 04019085. [CrossRef]

14. Sacks, R.; Eastman, C.; Lee, G.; Teicholz, P. *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers*, 3rd ed.; Wiley: Hoboken, NJ, USA, 2018; ISBN 978-1-119-28753-7.

15. Dashti, M.S.; RezaZadeh, M.; Khanzadi, M.; Taghaddos, H. Integrated BIM-Based Simulation for Automated Time-Space Conflict Management in Construction Projects. *Autom. Constr.* **2021**, *132*, 103957. [CrossRef]

16. Bortolini, R.; Formoso, C.T.; Viana, D.D. Site Logistics Planning and Control for Engineer-to-Order Prefabricated Building Systems Using BIM 4D Modeling. *Autom. Constr.* **2019**, *98*, 248–264. [CrossRef]

17. Moon, H.; Dawood, N.; Kang, L. Development of Workspace Conflict Visualization System Using 4D Object of Work Schedule. *Adv. Eng. Inform.* **2014**, *28*, 50–65. [CrossRef]

18. Popov, V.; Juocevicius, V.; Migilinskas, D.; Ustinovichius, L.; Mikalauskas, S. The Use of a Virtual Building Design and Construction Model for Developing an Effective Project Concept in 5D Environment. *Autom. Constr.* **2010**, *19*, 357–367. [CrossRef]

19. American Institute of Architects. *G202-2013 Project BIM Protocol*; AIA: Columbia, SC, USA, 2013.

20. Koutamanis, A. Dimensionality in BIM: Why BIM Cannot Have More than Four Dimensions? *Autom. Constr.* **2020**, *114*, 103153. [CrossRef]

21. Ding, L.; Zhou, Y.; Akinci, B. Building Information Modeling (BIM) Application Framework: The Process of Expanding from 3D to Computable ND. *Autom. Constr.* **2014**, *46*, 82–93. [CrossRef]

22. Staub-French, S.; Khanzode, A. 3D and 4D Modeling for Design and Construction Coordination: Issues and Lessons Learned. *Electron. J. Inf. Technol. Constr.* **2007**, *12*, 381–407.

23. Mazars, T.; Francis, A. Chronographical Spatiotemporal Dynamic 4D Planning. *Autom. Constr.* **2020**, *112*, 103076. [CrossRef]

24. Mesároš, P.; Smetanková, J.; Mandičák, T. The Fifth Dimension of BIM—Implementation Survey. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *222*, 012003. [CrossRef]

25. Charef, R.; Alaka, H.; Emmitt, S. Beyond the Third Dimension of BIM: A Systematic Review of Literature and Assessment of Professional Views. *J. Build. Eng.* **2018**, *19*, 242–257. [CrossRef]

26. Sheikhkhoshkar, M.; Pour Rahimian, F.; Kaveh, M.H.; Hosseini, M.R.; Edwards, D.J. Automated Planning of Concrete Joint Layouts with 4D-BIM. *Autom. Constr.* **2019**, *107*, 102943. [CrossRef]

27. Antwi-Afari, M.F.; Li, H.; Pärn, E.A.; Edwards, D.J. Critical Success Factors for Implementing Building Information Modelling (BIM): A Longitudinal Review. *Autom. Constr.* **2018**, *91*, 100–110. [CrossRef]

28. Zhou, Y.; Ding, L.; Wang, X.; Truijens, M.; Luo, H. Applicability of 4D Modeling for Resource Allocation in Mega Liquefied Natural Gas Plant Construction. *Autom. Constr.* **2015**, *50*, 50–63. [CrossRef]

29. Huang, T.; Kong, C.W.; Guo, H.L.; Baldwin, A.; Li, H. A Virtual Prototyping System for Simulating Construction Processes. *Autom. Constr.* **2007**, *16*, 576–585. [CrossRef]

30. Tran, S.V.-T.; Khan, N.; Lee, D.; Park, C. A Hazard Identification Approach of Integrating 4D BIM and Accident Case Analysis of Spatial–Temporal Exposure. *Sustainability* **2021**, *13*, 2211. [CrossRef]

31. Sloot, R.N.F.; Heutink, A.; Voordijk, J.T. Assessing Usefulness of 4D BIM Tools in Risk Mitigation Strategies. *Autom. Constr.* **2019**, *106*, 102881. [CrossRef]

32. Kim, K.; Lee, Y.-C. Automated Generation of Daily Evacuation Paths in 4D BIM. *Appl. Sci.* **2019**, *9*, 1789. [CrossRef]

33. Chen, P.-H.; Nguyen, T.C. A BIM-WMS Integrated Decision Support Tool for Supply Chain Management in Construction. *Autom. Constr.* **2019**, *98*, 289–301. [CrossRef]

34. Guerra, B.C.; Leite, F.; Faust, K.M. 4D-BIM to Enhance Construction Waste Reuse and Recycle Planning: Case Studies on Concrete and Drywall Waste Streams. *Waste Manag.* **2020**, *116*, 79–90. [CrossRef]

35. Costin, A.; Adibfar, A.; Hu, H.; Chen, S.S. Building Information Modeling (BIM) for Transportation Infrastructure—Literature Review, Applications, Challenges, and Recommendations. *Autom. Constr.* **2018**, *94*, 257–281. [CrossRef]

36. Hosseini, M.R.; Maghrebi, M.; Akbarnezhad, A.; Martek, I.; Arashpour, M. Analysis of Citation Networks in Building Information Modeling Research. *J. Constr. Eng. Manag.* **2018**, *144*, 04018064. [CrossRef]

37. Candelario-Garrido, A.; García-Sanz-Calcedo, J.; Reyes Rodríguez, A.M. A Quantitative Analysis on the Feasibility of 4D Planning Graphic Systems versus Conventional Systems in Building Projects. *Sustain. Cities Soc.* **2017**, *35*, 378–384. [CrossRef]

38. Hartmann, T.; Gao, J.; Fischer, M. Areas of Application for 3D and 4D Models on Construction Projects. *J. Constr. Eng. Manag.* **2008**, *134*, 776–785. [CrossRef]

39. Mahalingam, A.; Kashyap, R.; Mahajan, C. An Evaluation of the Applicability of 4D CAD on Construction Projects. *Autom. Constr.* **2010**, *19*, 148–159. [CrossRef]

40. Blanco, J.L.; Fuchs, S.; Parsons, M.; Ribeirinho, M.J. Artificial Intelligence: Construction Technology's next Frontier/McKinsey. Available online: https://www.mckinsey.com/business-functions/operations/our-insights/artificial-intelligence-construction-technologys-next-frontier (accessed on 23 April 2022).

41. Hartmann, T.; Trappey, A. Advanced Engineering Informatics—Philosophical and Methodological Foundations with Examples from Civil and Construction Engineering. *Dev. Built Environ.* **2020**, *4*, 100020. [CrossRef]

42. Ait-Lamallam, S.; Yaagoubi, R.; Sebari, I.; Doukari, O. Extending the IFC Standard to Enable Road Operation and Maintenance Management through OpenBIM. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 496. [CrossRef]

43. ISO. ISO 21500: 2021. Available online: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/07/57/75704.html (accessed on 16 April 2022).

44. Kelley, J.E. Critical-Path Planning and Scheduling: Mathematical Basis. *Oper. Res.* **1961**, *9*, 296–320. [CrossRef]

45. Boton, C. Conception de Vues Métiers Dans Les Collecticiels Orientés Service. Vers Des Multi-Vues Adaptées Pour La Simulation Collaborative 4D/ND de La Construction. Ph.D. Theses, Université de Lorraine, Nancy, France, 2013.

46. Heaton, J.; Parlikad, A.K.; Schooling, J. Design and Development of BIM Models to Support Operations and Maintenance. *Comput. Ind.* **2019**, *111*, 172–186. [CrossRef]

47. Santana, G. Classification of Construction Projects by Scales of Complexity. *Int. J. Proj. Manag.* **1990**, *8*, 102–104. [CrossRef]

48. Qazi, A.; Quigley, J.; Dickson, A.; Kirytopoulos, K. Project Complexity and Risk Management (ProCRiM): Towards Modelling Project Complexity Driven Risk Paths in Construction Projects. *Int. J. Proj. Manag.* **2016**, *34*, 1183–1198. [CrossRef]

49. Pellerin, R.; Perrier, N. A Review of Methods, Techniques and Tools for Project Planning and Control. *Int. J. Prod. Res.* **2019**, *57*, 2160–2178. [CrossRef]

50. Habibi, F.; Barzinpour, F.; Sadjadi, S.J. Resource-Constrained Project Scheduling Problem: Review of Past and Recent Developments. *J. Proj. Manag.* **2018**, *3*, 55–88. [CrossRef]

51. Sriprasert, E.; Dawood, N. Multi-Constraint Information Management and Visualisation for Collaborative Planning and Control in Construction. *J. Inf. Technol. Constr.* **2003**, *8*, 341–366.

52. Jaafari, A. Criticism of CPM for Project Planning Analysis. *J. Constr. Eng. Manag.* **1984**, *110*, 222–233. [CrossRef]

53. Harris, P.F.; McCaffer, P.R.; Edum-Fotwe, F. *Modern Construction Management*, 7th ed.; Wiley-Blackwell: Chichester, UK, 2013; ISBN 978-0-470-67217-4.

54. Line of Balance (LOB). Available online: https://www.designingbuildings.co.uk/wiki/Line_of_balance_(LOB) (accessed on 18 April 2022).

55. Mawdesley, M.; Askew, W.; Oreilly, M. *Planning & Controlling Construction Projects (Chartered Institute of Building): The Best Laid Plans*, 1st ed.; Prentice Hall: Essex, UK, 1997; ISBN 978-0-582-23409-3.

56. Halpin, D.W.; Martinez, L.-H. Real World Applications of Construction Process Simulation. In Proceedings of the 31st conference on Winter simulation: Simulation—A Bridge to the Future, Association for Computing Machinery, New York, NY, USA, 1 December 1999; Volume 2, pp. 956–962.

57. Planning and Analysis of Construction Operations/Wiley. Available online: https://www.wiley.com/en-us/Planning+and+Analysis+of+Construction+Operations-p-9780471555100 (accessed on 18 April 2022).

58. Martínez, J.C. STROBOSCOPE: State and Resource Based Simulation of Construction Processes. University of Michigan, USA. Available online: https://books.google.co.uk/books?id=xsceAQAAMAAJ (accessed on 18 April 2022).

59. Kartam, N.A.; Levitt, R.E.; Wilkins, D.E. Extending Artificial Intelligence Techniques for Hierarchical Planning. *J. Comput. Civ. Eng.* **1991**, *5*, 464–477. [CrossRef]

60. Soman, R.K.; Molina-Solana, M. Automating Look-Ahead Schedule Generation for Construction Using Linked-Data Based Constraint Checking and Reinforcement Learning. *Autom. Constr.* **2022**, *134*, 104069. [CrossRef]

61. Amer, F.; Golparvar-Fard, M. Modeling Dynamic Construction Work Template from Existing Scheduling Records via Sequential Machine Learning. *Adv. Eng. Inform.* **2021**, *47*, 101198. [CrossRef]

62. Jaklinović, K.; Đurasević, M.; Jakobović, D. Designing Dispatching Rules with Genetic Programming for the Unrelated Machines Environment with Constraints. *Expert Syst. Appl.* **2021**, *172*, 114548. [CrossRef]

63. Amer, F.; Jung, Y.; Golparvar-Fard, M. Transformer Machine Learning Language Model for Auto-Alignment of Long-Term and Short-Term Plans in Construction. *Autom. Constr.* **2021**, *132*, 103929. [CrossRef]

64. McKinney, K.; Fischer, M. Generating, Evaluating and Visualizing Construction Schedules with CAD Tools. *Autom. Constr.* **1998**, *7*, 433–447. [CrossRef]

65. Rolfsen, C.N.; Merschbrock, C. Acceptance of Construction Scheduling Visualizations: Bar-Charts, Flowline-Charts, Or Perhaps BIM? *Procedia Eng.* **2016**, *164*, 558–566. [CrossRef]

66. Retik, A.; Shapira, A. VR-Based Planning of Construction Site Activities. *Autom. Constr.* **1999**, *8*, 671–680. [CrossRef]

67. Sidani, A.; Matoseiro Dinis, F.; Duarte, J.; Sanhudo, L.; Calvetti, D.; Santos Baptista, J.; Poças Martins, J.; Soeiro, A. Recent Tools and Techniques of BIM-Based Augmented Reality: A Systematic Review. *J. Build. Eng.* **2021**, *42*, 102500. [CrossRef]

68. Casini, M. Chapter 9—Advanced Site Management Tools and Methods. In *Construction 4.0*; Casini, M., Ed.; Woodhead Publishing Series in Civil and Structural Engineering; Woodhead Publishing: Sawston, UK, 2022; pp. 471–521; ISBN 978-0-12-821797-9.

69. Goldratt, E.M. *Critical Chain*; North River Press: Great Barrington, MA, USA, 1997; ISBN 978-0-88427-153-6.

70. Jongeling, R.; Olofsson, T. A Method for Planning of Work-Flow by Combined Use of Location-Based Scheduling and 4D CAD. *Autom. Constr.* **2007**, *16*, 189–198. [CrossRef]

71. Womack, J.P.; Jones, D.T.; Roos, D. *The Machine That Changed the World: The Story of Lean Production—Toyota's Secret Weapon in the Global Car Wars That Is Now Revolutionizing World Industry*; Simon and Schuster: New York, NY, USA, 2007; ISBN 978-1-4165-5452-3.

72. Howell, G.A. *What Is Lean Construction?* Lean Construction Institute: Arlington, VA, USA, 1999.

73. Babalola, O.; Ibem, E.O.; Ezema, I.C. Implementation of Lean Practices in the Construction Industry: A Systematic Review. *Build. Environ.* **2019**, *148*, 34–43. [CrossRef]

74. Ballard, H.G. The Last Planner System of Production Control. Ph.D. Thesis, University of Birmingham, Birmingham, UK, 2000.

75. Murguia, D.; Brioso, X.; Pimentel, A. Applying Lean Techniques to Improve Performance in the Finishing Phase of a Residential Building. In Proceedings of the 24th Annual Conference of the International Group for Lean Construction, Boston, MA, USA, 18–24 July 2016; pp. 43–52.

76. Adamu, S.; Howell, G.; Abdulhamid, R. Adapting Lean Construction Tecniques in Nigerian Construction Industry. *Int. J. Sci. Eng. Res.* **2012**, *3*, 1–11.

77. Alsehaimi, A.O.; Tzortzopoulos, P.; Koskela, L.J. Last Planner System: Experiences from Pilot Implementation in the Middle East. In Proceedings of the 17th Annual Conference of the International Group for Lean Construction, Taipei, Taiwan, 15–17 July 2009; pp. 53–65.

78. Alarcón, L.F.; Diethelmand, S.; Rojo, O. Collaborative Implementation of Lean Planning Systems in Chilean Construction Companies. In Proceedings of the Tenth Annual Conference of the International Group for Lean Construction (IGLC-10), Gramado, Brazil, 6–8 August 2002; pp. 1–11.

79. Sanni-Anibire, M.O.; Mohamad Zin, R.; Olatunji, S.O. Causes of Delay in the Global Construction Industry: A Meta Analytical Review. *Int. J. Constr. Manag.* **2020**, *22*, 1395–1407. [CrossRef]

80. Michalski, A.; Głodziński, E.; Böde, K. Lean Construction Management Techniques and BIM Technology—Systematic Literature Review. *Procedia Comput. Sci.* **2022**, *196*, 1036–1043. [CrossRef]

81. ISO. ISO 19650-1: 2018. Available online: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/80/68078.html (accessed on 16 April 2022).

82. Sanders, S.R.; Thomas, H.R. Factors Affecting Masonry-Labor Productivity. *J. Constr. Eng. Manag.* **1991**, *117*, 626–644. [CrossRef]

83. Chavada, R.; Dawood, N.; Kassem, M. Construction Workspace Management: The Development and Application of a Novel ND Planning Approach and Tool. *Electron. J. Inf. Technol. Constr.* **2012**, *17*, 213–236.

84. Trebbe, M.; Hartmann, T.; Dorée, A. 4D CAD Models to Support the Coordination of Construction Activities between Contractors. *Autom. Constr.* **2015**, *49*, 83–91. [CrossRef]

85. Tran, S.; Ali, A.K.; Khan, N.; Lee, D.; Park, C. A Framework for Camera Planning in Construction Site Using 4D BIM and VPL. *ISARC Proc.* **2020**, *37*, 1404–1408.

86. Braun, A.; Tuttas, S.; Borrmann, A.; Stilla, U. A Concept for Automated Construction Progress Monitoring Using BIM-Based Geometric Constraints and Photogrammetric Point Clouds. *J. Inf. Technol. Constr.* **2015**, *20*, 68–79.

87. Sriprasert, E.; Dawood, N. Next Generation of Construction Planning and Control System: The Lewis Approach. Available online: https://www.semanticscholar.org/paper/NEXT-GENERATION-OF-CONSTRUCTION-PLANNING-AND-SYSTEM-Sriprasert-Dawood/b34eb601bbae61605e89f563449aa3a72f6c019d (accessed on 20 April 2022).

88. Han, S.; Bouferguene, A.; Al-Hussein, M.; Hermann, U. (Rick) 3D-Based Crane Evaluation System for Mobile Crane Operation Selection on Modular-Based Heavy Construction Sites. *J. Constr. Eng. Manag.* **2017**, *143*, 04017060. [CrossRef]

89. Tan, Y.; Fang, Y.; Zhou, T.; Gan, V.J.L.; Cheng, J.C.P. BIM-Supported 4D Acoustics Simulation Approach to Mitigating Noise Impact on Maintenance Workers on Offshore Oil and Gas Platforms. *Autom. Constr.* **2019**, *100*, 1–10. [CrossRef]

90. Golparvar-Fard, M.; Peña-Mora, F.; Arboleda, C.A.; Lee, S. Visualization of Construction Progress Monitoring with 4D Simulation Model Overlaid on Time-Lapsed Photographs. *J. Comput. Civ. Eng.* **2009**, *23*, 391–404. [CrossRef]

91. Said, H.; El-Rayes, K. Automated Multi-Objective Construction Logistics Optimization System. *Autom. Constr.* **2014**, *43*, 110–122. [CrossRef]

92. Chin, S.; Yoon, S.; Choi, C.; Cho, C. RFID+4D CAD for Progress Management of Structural Steel Works in High-Rise Buildings. *J. Comput. Civ. Eng.* **2008**, *22*, 74–89. [CrossRef]

93. Hewage, K. Sustainable Construction: An Information Modelling Approach for Waste Reduction. In Proceedings of the International Conference on Building Resilience, Kandalama, Sri Lanka, 19–21 July 2011.

94. Won, J.; Cheng, J.C.P. Identifying Potential Opportunities of Building Information Modeling for Construction and Demolition Waste Management and Minimization. *Autom. Constr.* **2017**, *79*, 3–18. [CrossRef]

95. Bakchan, A.; Guerra, B.C.; Faust, K.M.; Leite, F. BIM-Based Estimation of Wood Waste Stream: The Case of an Institutional Building Project. In *Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation*; American Society of Civil Engineers: Reston, VA, USA, 2019; pp. 185–192. [CrossRef]

96. Hardin, B.; McCool, D. *BIM and Construction Management: Proven Tools, Methods, and Workflows*, 2nd ed.; Wiley: Hoboken, NJ, USA, 2015; ISBN 978-1-118-94276-5.

97. Gebrehiwet, T.; Luo, H. Analysis of Delay Impact on Construction Project Based on RII and Correlation Coefficient: Empirical Study. *Procedia Eng.* **2017**, *196*, 366–374. [CrossRef]

98. Sriprasert, E.; Dawood, N. Genetic Algorithms for Multi-Constraint Scheduling: An Application for the Construction Industry. In Proceedings of the 20th International Conference on Construction IT: Construction IT Bridging the Distance, Auckland, New Zealand, 23–25 April 2003.

99. Susanto, N.; Putranto, T.T. Stakeholder Interactions Model of Groundwater Management in Semarang City/Indonesia. *Int. J. Geomate* **2018**, *15*, 170–177. [CrossRef]

100. Amorocho, J.A.P.; Hartmann, T. Reno-Inst: An Ontology to Support Renovation Projects Planning and Renovation Products Installation. *Adv. Eng. Inform.* **2021**, *50*, 101415. [CrossRef]

101. Singh, Y.; Abdelhamid, T.; Mrozowski, T.; El-Gafy, M.A. Investigation of Contemporary Performance Measurement Systems for Production Management of Renovation Projects. *J. Constr. Eng.* **2014**, *2014*, 1–9. [CrossRef]

102. Aldanondo, M.; Barco-Santa, A.; Vareilles, E.; Falcon, M.; Gaborit, P.; Zhang, L. Towards a BIM Approach for a High Performance Renovation of Apartment Buildings. In *Product Lifecycle Management for a Global Market*; Fukuda, S., Bernard, A., Gurumoorthy, B., Bouras, A., Eds.; Springer: Berlin/Heidelberg, Germany, 2014; pp. 21–30.

103. Doukari, O.; Lynn, T.; Rosati, P.; Egli, A.; Krinidis, S.; Angelakoglou, K.; Sougkakis, V.; Tzovaras, D.; Kassem, M.; Greenwood, D. RINNO: Transforming Deep Renovation through an Open Renovation Platform. In Proceedings of the ICDS The Fifteenth International Conference on Digital Society, Nice, France, 18–22 July 2021.

104. Lynn, T.; Rosati, P.; Egli, A.; Krinidis, S.; Angelakoglou, K.; Sougkakis, V.; Tzovaras, D.; Kassem, M.; Greenwood, D.; Doukari, O. RINNO: Towards an Open Renovation Platform for Integrated Design and Delivery of Deep Renovation Projects. *Sustainability* **2021**, *13*, 6018. [CrossRef]

105. Sacks, R.; Koskela, L.; Dave, B.A.; Owen, R. Interaction of Lean and Building Information Modeling in Construction. *J. Constr. Eng. Manag.* **2010**, *136*, 968–980. [CrossRef]

106. Kanan, R.; Elhassan, O.; Bensalem, R. An IoT-Based Autonomous System for Workers' Safety in Construction Sites with Real-Time Alarming, Monitoring, and Positioning Strategies. *Autom. Constr.* **2018**, *88*, 73–86. [CrossRef]

107. Barlish, K.; Sullivan, K. How to Measure the Benefits of BIM—A Case Study Approach. *Autom. Constr.* **2012**, *24*, 149–159. [CrossRef]

108. Matthews, J.; Love, P.E.D.; Mewburn, J.; Stobaus, C.; Ramanayaka, C. Building Information Modelling in Construction: Insights from Collaboration and Change Management Perspectives. *Prod. Plan. Control* **2018**, *29*, 202–216. [CrossRef]

109. Ilozor, B.; Kelly, D. Building Information Modeling and Integrated Project Delivery in the Commercial Construction Industry: A Conceptual Study. *J. Eng. Proj. Prod. Manag.* **2012**, *2*, 23–26. [CrossRef]

110. Collins, W.; Parrish, K. The Need for Integrated Project Delivery in the Public Sector. In Proceedings of the Construction Research Congress 2014: Construction in a Global Network, Atlanta, GA, USA, 19–21 May 2014; pp. 719–728. [CrossRef]

111. Vass, S.; Gustavsson, T.K. Challenges When Implementing BIM for Industry Change. *Constr. Manag. Econ.* **2017**, *35*, 597–610. [CrossRef]

112. Stanford University Protégé. Available online: https://protege.stanford.edu/ (accessed on 28 April 2022).

113. Designing Buildings Disruption Claims in Construction. Available online: https://www.designingbuildings.co.uk/wiki/Disruption_claims_in_construction (accessed on 17 February 2022).

114. Estate Regeneration—Building out Disruption. Available online: http://thoughtleadership.trowers.com/estate-regeneration/building-out-disruption/ (accessed on 17 February 2022).

115. Chaves, F.J.; Tzortzopoulos, P.; Formoso, C.T.; Biotto, C.N. Building Information Modelling to Cut Disruption in Housing Retrofit. In *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*; Thomas Telford Ltd: London, UK, 2017; Volume 170, pp. 322–333. [CrossRef]

116. Bedrick, J.; Builders, W. Organizing the Development of a Building Information Model. *Am. Inst. Archit.* **2008**, *9*, 4.

117. Leite, F.; Akcamete, A.; Akinci, B.; Atasoy, G.; Kiziltas, S. Analysis of Modeling Effort and Impact of Different Levels of Detail in Building Information Models. *Autom. Constr.* **2011**, *20*, 601–609. [CrossRef]