buildings

MDPI

Article

Dynamic Spatiotemporal Scheduling for Construction Building Projects

Stéphane Morin-Pépin * and Adel Francis

Construction Engineering Department, École de Technologie Supérieure (ÉTS), Montreal, QC H3C 1K3, Canada; adel.francis@etsmtl.ca
* Correspondence: stephane.morin-pepin.1@ens.etsmtl.ca

Abstract: For building projects, the manager is responsible for coordinating the work of subcontractors at the construction site. This includes operations, material flows, and storage. In summary, one of their main roles is to ensure smooth team rotation, maintain fluid circulation, and avoid congestion or relaxation on the site. However, traditional tools lack the ability to consider the planning and management of worksite spaces when calculating the execution schedule and critical path. Consequently, three-week planning is usually carried out separately on independent plans, often using spreadsheets. In addition, a construction site is highly dynamic and mobile in nature, and the positioning of resources and workers can change daily. This makes the management of available space even more complex, and effective space management becomes an imperative. To address this challenge, this paper develops visual dynamic artifacts that present different operation types. The methodology and the conceptual framework facilitate the calculation of the Occupancy Rate (OR) that enables construction project managers to create simple yet dynamic spatiotemporal models of the construction schedule. By incorporating factors such as crew turnover and occupancy evolution, managers can simplify the calculation process and effectively optimize construction work by utilizing site occupancy rates. In summary, this paper presents the Dynamic Model of the Occupancy Rate Schedule (DMORS), a methodology developed through design science. This model utilizes created artifacts representing various operation types to ensure accurate calculations of dynamic occupancy by floor and sector in a site. Consequently, it enables the construction of a more realistic schedule based on critical space ideologies. The DMORS enables managers to use the OR for different floors and sectors of a site, allowing for better space management. A proof of concept demonstrates that this tool can enhance the efficiency and productivity of construction projects by optimizing crew schedules and resource allocation based on site OR.

Keywords: construction planning; space planning; chronographic modeling; occupation rate; site occupation; dynamic modeling; building construction

Citation: Morin-Pépin, S.; Francis, A. Dynamic Spatiotemporal Scheduling for Construction Building Projects. *Buildings* **2024**, *14*, 3139. https://doi.org/10.3390/buildings14103139

Academic Editors: Antonio Caggiano and Jorge Lopes

Received: 20 June 2024
Revised: 6 September 2024
Accepted: 26 September 2024
Published: 1 October 2024

1. Introduction

Construction project planning techniques primarily use Gantt–Precedence logic to model activities and their dependencies. The Gantt–Precedence diagram defines activities on a time scale, allocates resources, and handles constraints. However, several limitations make this method not well-suited for the scheduling and management of building construction sites. These limitations include imprecise precedence logic with the reverse critical path, potential congestion, overlooked space utilization, site traffic, and complex graphics rendering, highlighting difficulties in visually interpreting dependency lines due to their density and overlap.

The nature of building projects makes site construction a dynamic process: workers are constantly on the move, materials are delivered and used, and machines go in and out of the construction site [1–4]. Riley [1] has partially represented and categorized this dynamic aspect of construction sites. However, as work progresses, the available space tends to decrease, making it difficult to access.

Linear diagram methods provide partial solutions by ensuring resource linearity, making them suitable for linear projects like infrastructure but less effective for complex building projects with many unique activities. Repetitive models, which handle recurring tasks across multiple units or floors, are more apt for vertical and horizontal building projects. They calculate specialty team requirements based on the duration and total time available for tasks. Combining repetitive modeling with space planning methods improves efficiency by linking spatial and temporal aspects, promoting optimal site usage, and ensuring efficient workforce rotation. Space planning is crucial as construction involves workers moving to different sites, unlike manufacturing where work comes to the workers. Neglecting workspace considerations can lead to site congestion and conflicts.

Spatiotemporal planning emerges as a more suitable scheduling model because it concurrently considers activities, resources, and spaces. Akinci and Fischer [5] noted that the majority of trade contractors know the space they will need for future work. They also mention that there is no system that allows the general contractor to collect this information and integrate it into the work planning, so they cannot consider their spatiotemporal needs when designing the construction schedule. To remedy this problem, they discussed a generic model that would collect spatiotemporal information on the working methods of trade contractors. Still, according to Akinci and Fischer [5], such a model would offer two (2) advantages: (i) the possibility to study the space required for each working method and (ii) the possibility of reusing the same spatiotemporal information for all activities that use the same working methods.

Guo [6] have combined Gantt and AutoCAD to develop a process for detecting and resolving space conflicts on the construction site. According to them, this CAD system allows managers to indicate prioritization criteria in order to dynamically perform and detect space conflicts arising from planning and propose a solution on the project's CAD plans. This decision support system therefore makes it possible to solve this complex problem more efficiently and accurately.

Mallasi [7] raised four (4) specific issues in spatiotemporal planning: (i) the representation of execution strategy, (ii) simulations of construction progress, (iii) three-dimensional workspace planning, and (iv) the analysis of spatiotemporal connections. He developed Critical Space–time Analysis (CSA), which is a reasoning mechanism that minimizes the criticality of spatiotemporal conflicts. He introduced the concept of "workspace competition" to minimize congestion between activities. The evaluation of the CFS is undertaken with the help of PECASO, a prototype application that uses a multi-criteria function to assess the severity of conflicts. The objective of its PECASO-CSA approach is to make managers aware of spatiotemporal planning and to improve their confidence when using 4D simulations to communicate the construction schedule.

Chua et al. [8] have proposed a methodology that distinguishes between several classes of conflicts; they mainly seek to show the links between space conflicts and congestion on construction sites. To do this, they introduced two (2) indicators that can be used as a complement to 4D-CAD analyses: (i) dynamic space interference (DSI), which quantifies interference when there is a conflict between activities, and (ii) a congestion penalty indicator (CPI) which evaluates, analyzes, and compares the feasibility of several schedules.

Bansal [9] mentioned that geometric and semantic information are essential for workplace planning. In addition, with a 3D model of the building with its surroundings, doing a 4D simulation, and the ability to do geospatial analysis in a single platform, this model can be an important asset to design planning by work location. So, he integrated GIS with 4D simulations to create a 3D-GIS environment. According to the author, this environment makes it possible to identify and resolve space conflicts, from the design of plans to construction planning; changes in planning are then made in the 3D-GI environment directly.

Said and El-Rayes [10] developed Congested Construction Logistics Planning, a model that uses genetic algorithms to optimize the use of interior space in a building under construction. According to them, this model helps minimize logistics costs while minimizing the impact of material storage on the construction schedule. The genetic algorithm is used to optimize four categories of variables: (i) material procurement, (ii) material storage plans, (iii) the positioning of temporary facilities, and (iv) the planning of noncritical activities. In a later search, Said and Lucko [11] identified two (2) gaps in site planning research. First, the concept of margins is not well defined in the research and, second, there are no measures to quantify the availability of workspaces. In order to remedy these shortcomings, Said and El-Rayes [10] have determined margins on work and productivity teams in order to develop and calculate a new margin that allows measuring of the flexibility present in the planning by work location.

Mirzaei et al. [12] have developed a new approach, which they believe can dynamically detect spatiotemporal conflicts. First, the workspace of the teams is determined by their movements within the different sectors. Subsequently, this information is inserted into a BIM-4D simulation in order to detect, calculate, and dynamically display the positioning and size of conflicts between work teams during construction.

However, most of these space planning optimization processes rely on deterministic or stochastic optimization techniques, which are not sufficiently viable for application to construction schedules. The multitude of parameters involved makes purely algorithmic optimization impractical.

Kenley and Seppänen [13,14] and Olivieri et al. [15] have proposed the Location-Based Management System (LBMS), which aims to ensure that tasks are carried out in a continuous flow. The advantage of a schedule using the LBMS is to have a clear representation of the sequence of work, to visualize the sectors available on the site and to directly observe the effect of deviations on the progress of the work. The LBMS focuses on observing work teams evolving through the different sectors of the site. Francis and Miresco [16] stated that the focus is no longer on the critical path, but rather on production efficiency. The network set the point-topoint relation that takes into account: (i) external logic, to make the links between the activities that follow one another in a sector and (ii) internal logic, which makes it possible to calculate the duration of an activity based on the quantities and the rate of production. This facilitates schedule optimization, which is carried out using the following tools (in order): (i) the change in the production rate by changing available resources, (ii) the change in the production rate by changing the scope of work, (iii) the change in the location sequence, (iv) the change in the team sequence, and (v) the division of tasks.

For its part, chronographic modeling is focused on the concepts of space planning and on the need to develop management and planning applications better adapted to the field of construction. Its main attraction lies in its graphic ability to present useful information for the management of construction projects. From its conceptual framework and graphic protocol [17,18], the result is a series of tabular and graphical models generating displays adapted to different types of projects, various specialties, and all situations that may arise during a construction project. The spatiotemporal timelines thus produced are designed specifically to meet the needs of each stakeholder of a construction project, adapting the visualization to facilitate the monitoring of the project by displaying the right information, clearly and precisely [19,20].

The effective management of space and movement on a construction site is crucial for ensuring the smooth progress of work. To achieve this, a system based on dynamic spatiotemporal representations of the site is a promising solution. Such a system would facilitate the dynamic utilization of space, thereby preventing both underutilization and congestion on the site. However, the development of this system requires a straightforward approach for calculating the occupancy rate and determining which spaces are occupied or available. Although there are existing research projects and systems focused on the spatiotemporal representation of planning, as well as those aimed at representing, calculating, and optimizing available space on a construction site, few of these projects address both aspects simultaneously.

Graphical spatiotemporal solutions integrate graphical, procedural, and algorithmic elements. By amalgamating spaces and operations, this approach ensures the continuous use of spaces and teams, facilitating linear production. The proposed methodology prioritizes the critical space on the critical path of activities, enhancing scheduling efficiency. This study aims to develop visual dynamic artifacts that present different operation types. The proposed Dynamic Model of the Occupancy Rate Schedule (DMORS) using a design science methodology enables managers visualize the position of the work teams and the recourses inside each sector, which permits the calculation of the occupancy rates for different floors and sectors of a site, allowing for better space management. Table 1 shows different planning methods presented in this literature review and compares their approach to managing several aspects of space planning, space occupation, and conflict detection. This comparison supports the necessity of considering the occupancy rate and highlights this study's contribution.

Table 1. Comparison of planning methods and their capabilities.

Planning Methods	**Work Schedule Visualization**	**Work Team Location and Rotation Visualization**	**Space Conflict Detection**	**Operation Occupation Rate on the Site**	**4D Simulation**	**Modeling Different Types of Operation on the Site**
Gantt [21,22]	**Yes**	**No**	**No**	**No**	**Not adapted** Do not represent objects in space	**No**
Gantt and AutoCAD [6]	**Yes** With Gantt	**Partially** Transportation optimization process only	**Yes** Transportation optimization process only	**Partially** Transportation optimization process only	**Partially** With CAD system	**No**
Multi-objective optimization model/logistics planning [10,11]	**Yes** Linear-based method	**Partially** Linear-based method	**No**	**Yes** Pre-determined values	**No**	**No**
Dynamic 4D-BIM–based approach [12]	**Yes** With Gantt	**Yes** With execution alternatives	**Yes** Dynamic detection of conflicts with labor movements in the workspace	**Partially** Labor workspace only	**Partially** Gantt linked to BIM3D model	**No**
Space planning (automation) [5]	**Yes** With Gantt	**Partially** With 4D simulation	**Partially** No graphical representation	**Partially** For specific equipment only	**Yes** Space-loaded production model 4D simulations	**No**
Space planning (graphical modeling) [1–4]	**Yes** Own schedule technique	**Yes** Graphical work-area patterns	**Yes** Direct observation	**Yes** Mathematical equations and graphical patterns	**No**	**Yes** Graphical work-area patterns
Takt-time [23,24]	**Yes** Linear planning	**Yes** Manually drawn on the drawings	**No**	**No**	**Yes** Takt schedule linked to 3DBIM model	**No**

Table 1. *Cont.*

Planning Methods	Work Schedule Visualization	Work Team Location and Rotation Visualization	Space Conflict Detection	Operation Occupation Rate on the Site	4D Simulation	Modeling Different Types of Operation on the Site
LBMS [13–15]	**Yes** Linear planning	**No**	**No**	**No**	**Yes** LBMS linked to 3DBIM model	**No**
Chronographic modeling [16–20,25–27]	**Yes** Multiple graphical modeling	**Yes** Several spatiotemporal models	**Yes** Graphical detection	**Yes** Basis of representation on the schedule	**Yes** Chronographic modeling linked to 3DBIM model	**No**
DMORS ([28] and current paper)	**Yes** With chronographic modeling	**Yes** Specific dynamic artifacts for the work teams and recourses on the schedule	**Yes** Specific dynamic artifacts for the work teams and recourses on the schedule	**Yes** Dedicated graphical and calculation methodology	**Yes** Same as chronographic modeling	**Yes** Visual dynamic artifacts for different operation types

2. Objectives and Limitations

2.1. Research Goal and Objectives

The aim of this research is to develop a construction planning system which combines the graphic capabilities of chronographic modelling [19,25–27] and the dynamic calculation of the occupancy rate. Such a system would optimize space utilization on the job site, while reducing travel and improving safety on construction sites, and improve the integration of the supply chain into the construction process based on Lean methods. This can include accurate delivery planning, the effective coordination of different suppliers and subcontractors, and the use of supply chain management platforms.

The main strength of the proposed model is to allow construction managers to anticipate the available and occupied space on the site at the same time as planning construction. This ability to combine the two allows managers to obtain additional information, in this case the occupancy rate, while limiting increasing their workloads. This paper follows the work presented in Morin-Pépin and Francis [28] which presents standard artifacts to represent the static occupation of occupancy type (OT) in different sectors.

Thus, the main objective of this article is to propose a methodology based on the dynamic spatiotemporal modeling of the work in order to calculate and anticipate the occupancy rate (OR) of the site. This OR will allow the manager to use it as a criterion for leveling the construction schedule. Based on chronographic modelling, the methodology proposed in this article aims to perform a dynamic spatiotemporal representation of the positioning of work teams and resources on the site and to anticipate the space they will need to carry out the work.

2.2. Constrains and Limits

The proposed system requires the constant collection and processing of a lot of information in order to correctly represent the occupancy rate. It will therefore be necessary to develop a specific application. This will allow, among other things, the testing of the DMORS on real projects. Also, it will be necessary to determine a procedure that will allow the tracking of all the changes that occur during construction and to update the DMORS and compare the planning to the real occupancy rate.

3. Research Methodology

The methodology used in this research is based on the seven (7) guidelines presented by Hevner et al. [29]. It is constituted of the 10 steps that are presented in Figure 1. It must be noted that steps 3.1 to 3.3 of this methodology were presented in detail in Morin-Pépin and Francis [28], so they will not be included in this paper. Also, step 3.7 will be presented in detail in a future publication. So, only steps 3.4 to 3.6 will be discussed in this paper.

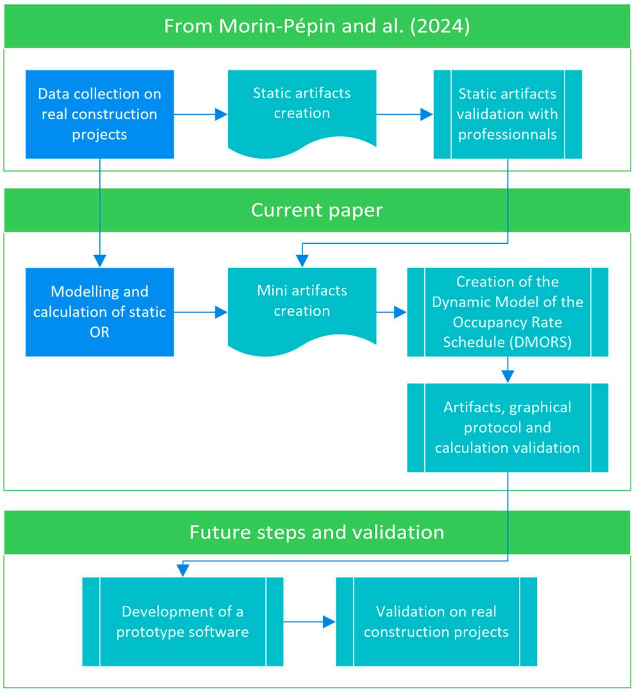

Figure 1. Research methodology [28].

3.1. Data Collection on Real Construction Projects

To enhance the planning quality of construction projects, this research employed an empirical methodology. This is shown in Figure 1, where the initial phase involved on-site visits to collect data on the positions and spatial occupancy of all work teams and resources involved in the construction process.

3.2. Static Artifacts Creation

To enhance the planning quality of construction projects, this research employed an empirical methodology. As shown in Figure 1, the initial phase involved on-site visits to collect data on the positions and spatial occupancy of all work teams and resources involved in the construction process.

3.3. Static Artifacts Validation

A first validation was carried out with workshops with industry professionals in order to validate the static artifacts that represent the positioning and occupancy that the occupancy types have in the sector where they are positioned. Once validated, these static artifacts become an essential part of the occupancy rate calculation process presented in this article, as they allow managers to visualize the space occupied by the OTs and specify which parameter will be critical to the OR's calculations.

3.4. Modeling and Calculation of Static OR and Mini Artifacts

The analysis and optimization process begin as soon as the manager positions resources and work teams, called OT in this paper, in a sector, and this process continues as other OTs are positioned. It is therefore necessary to display the relevant information that will allow managers to make a proper analysis of the OR. To do this, several levels of the OR will be required, starting with the calculation of an OR for each of the sectors individually. This will then allow the calculation of the OR for an entire floor and then for the entire construction site.

3.5. The Creation of the Dynamic Model of the Occupancy Rate Schedule (DMORS)

The representation of the dynamic spatiotemporal evolution of the occupancy rate is be carried out through chronographic modeling, by adding the OR as an additional layer of information to the different representations of the chronographic schedules. For this, a detailed procedure is proposed and mini artifacts were designed to represent the OT and the OR on the DMORS. This will add the ability to use this dynamic representation of the OR to visualize and identify the over- and underutilized sectors as the project manager builds the project's schedule.

3.6. The Validation of the Created Artifacts, Graphical Protocol, and Calculation Methods through Workshops

The validation process was carried out using the example project. As a proof of concept, a DMORS was made for this project to show the optimization capabilities.

3.7. Validation on Real Construction Projects

Finally, following the development of a prototype software, a third validation will take place on real construction projects to test the capacity and effectiveness of the DMORS to optimize the utilization of available space on construction sites.

4. Modeling and Calculation of Static Occupancy Rates (ORs) and Mini Artifacts

The first essential element of this research is to determine and classify all the elements that will occupy space during the construction phase. Resources, like the building materials and the machinery, are generally the first thing that come to mind when we talk about the occupation of space. But a project manager must also plan and reserve the necessary space needed by the work team to adequately execute their tasks. For this reason, the term OT is used in this research to include all the items that can occupy space during construction and to calculate the specific OR for each. The procedure presented in this paper uses the parameters of the OT and of the sectors (Figure 2) to calculate the static and dynamic OR that will enable the optimization of the construction workflow.

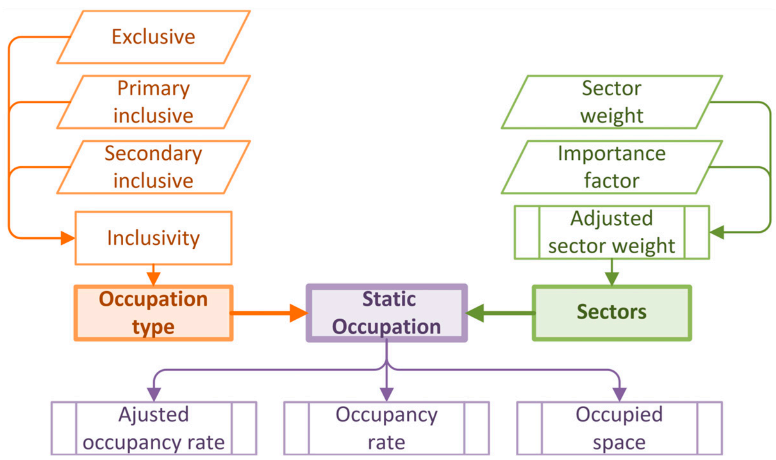

Figure 2. Properties of static occupations.

The first step is to calculate the occupancy rates for each OT and for each of the sectors present on the construction site and, in a second step, to calculate the occupancy rate for a part of the construction site, for example, for a complete floor. The fictitious project, presented in Figure 3, will be used to demonstrate the calculations in the next sections.

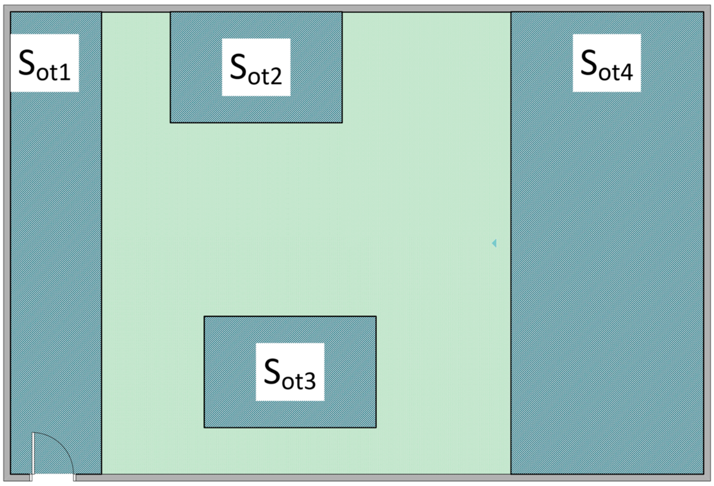

Figure 3. Area containing several OT.

4.1. *The Inclusivity of an OT*

Once an OT is placed in a sector, it becomes a static occupation, which allows the determination and calculation of the parameters shown in Figure 2. The first parameter is inclusivity, which indicates the priority of the OT in the sector and indicates whether other OTs may be present in the same area at the same time. An "exclusive" occupation means that it should be the only OT present in a sector, like the plaster sanding in the example project shown in Figure 4. An "inclusive primary" occupation means that the OT is the top priority in the sector, but other OTs can be present if there is sufficient space. And finally, a "secondary inclusive" occupation as a lower priority, meaning that if there is not sufficient space in the sector, this OT should be placed in another sector.

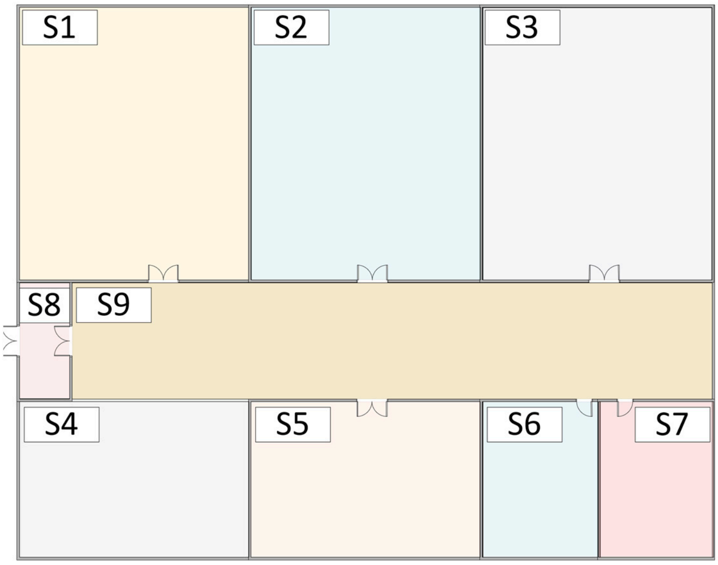

Figure 4. Example project.

4.2. *Static Occupation*

As for the space occupied by an OT, it can be determined in two (2) ways. The simplest is to directly use the dimensions of the OT, as in the example, where a bundle of 4 ft × 8 ft (1.2 m × 2.4 m) plywood board occupies about 3 m^2. Otherwise, in the context of OTs that represent work teams, the space occupied will often depend on the dimensions of the room in which the work will be carried out. A good example is the installation of the gypsum board on the wall, which depends on the wall perimeter or the installation of the floor tiles, which will probably occupy all the available space. Subsequently, the OR will be obtained by dividing the space occupied by the OT by the total area of the sector in which the OT is located. Note that the adjusted occupancy rate will be discussed later in this paper.

The first set of ORs to be calculated are the ones for each sector present on a floor or a part of the site. Whether there is only one OT or several in the same sector, as shown in Figure 3 where there are four (4) OTs, the area occupied by each OT, numbered from S_{ot1} to S_{ot4}, must first be added together to obtain the area occupied (S_{os}) in the sector (Equation (1). Next, the occupancy rate ($\%_{os}$) is calculated by dividing this occupied area by the total area of the sector (S_m) where the occupancy types are present (Equation (2)).

$$S_{os} = \sum_{i=1}^{n} S_{oti} \tag{1}$$

where n = all OTs present in the area

$$\%_{os} = \frac{S_{os}}{S_m} \times 100\% \tag{2}$$

This provides an initial source of information and analysis on the state of the space that should be available on the site. Indeed, if we look at the example DMORS in the Section 5.5, the sector S7 between days 32 and 34 is over encumbered, with an OR of 123%. This is because, in this sector, there is space reserved for the suspended ceiling installation teams (129 m^2), the suspended ceiling materials themselves (19.4 m^2), and the recycling container (10 m^2). This is more than the available space (129 m^2). The project manager will therefore have a decision to make and prioritize some of the OTs, because they cannot all be present in this sector at the same time.

4.3. The Occupancy Rate for a Part of the Site

The second and last step is the calculation of the occupancy rate for a part of the project. This depends mainly on the needs of the manager, whether he needs the OR of a floor, a phase, or the project as a whole.

4.3.1. The Weight of the Sector

During a construction project, not all sectors have the same importance. To indicate this importance, the relative weight of each sector is calculated for the floor where it is positioned. Demonstrated by Equation (3) (where n = number of sectors on the floor), the weight of a sector (Ws_s) corresponds to the maximum surface area of the sector (S_m) divided by the sum of the maximum surface areas of all the sectors included on the floor. This will give the relative weight of each sector in relation to that part of the construction site. According to Table 2, Sector 1 (S1) has a total area of 225 m^2, while the sum of the maximum areas of all the sectors on the floor is 1350 m^2. Thus, the weight of S1 represents 16.7% of the total area of the floor.

$$Ws_{si} = \frac{S_{mi}}{\sum_{j=1}^{n} S_{mj}} \times 100\% \tag{3}$$

Table 2. The weight of sectors for a part of a building.

Sector	P_m (m)	S_m (m^2)	Ws_s (%)	If_s	Wsa_s (%)
1	60	225	16.7%	1	9.7%
2	60	225	16.7%	1	9.7%
3	60	225	16.7%	1	9.7%
4	32.4	64	9.6%	2	5.5%
5	32.4	64	9.6%	2	5.5%
6	46	129	4.7%	1.5	8.4%
7	46	129	4.7%	2.5	13.6%
8	20	21	1.6%	3	2.7%
9	90.8	268	19.9%	3	34.7%
Total		1350	100%		100%

4.3.2. Importance Factor

The weight calculated in the previous section considers that each of the sectors present on the floor has the same importance. However, as mentioned by Francis [26], some sectors may be more important than others. The manager will determine this importance according to his priorities and the configuration of the floor. An importance factor (If_s) is therefore assigned to each sector. Starting with 1 for the sectors with the lowest importance, the If_s increase as the space represented by a sector becomes more important to the good progress of the work. Thus, in the example presented, Sector 8 (entrance hall) and Sector 9 (main corridor) are essential for the circulation of work crews and materials, so their Ifs are the highest (If_s = 3), while Sectors 1, 2, and 3 have an If_s = 1, because they are the least important. Note that, for now, there is no limit to the theoretical maximum of the importance factor. It is left to the project manager's discretion to set the maximum limits of the importance factor.

4.3.3. Adjusted Sector Weight

This importance factor will then be used in Equation (4) (where n = number of sectors on the floor) to vary the weight of the sector (Ws_a) according to this importance. The maximum available area of a sector (S_m) is multiplied by the importance factor (If_s) of that same sector, and then divided by the sum of the multiplication of the maximum available areas and the importance factors of all the sectors available on the floor. The weight of the least important sectors will thus be decreased, while the weight of the most important sectors will be increased. As shown in Table 1, Sector 1, which is one of the least important, which has an initial weight of Ws_s = 16.7% on the floor, ends up with an adjusted weight of Wsa_s = 9.7%. However, Sector 9, which has an initial weight of Ws_s = 19.9% and is the most important (If_s = 3), obtains an adjusted weight of Wsa_s = 34.7%.

$$Wsa_{si} = \frac{(S_{mi} \times If_{si})}{\sum_{j=1}^{n}\left(S_{mj} \times If_{sj}\right)} \times 100\% \quad (4)$$

4.3.4. The OR for a Level, for Each Period

The calculation of the OR for a certain part of the construction site ($\%_{part}$) is the third step in the process of calculating OR. Whether it is for a floor or the entire construction site, for this step, Equation (5) is used. It will be necessary to calculate the OR of each of the sectors in relation to the desired part of the site (Ws_s). The same equation is used to calculate the adjusted occupancy rate ($\%_{parta}$) by using the adjusted weight (Wsa_s) instead of the regular weight.

$$\%_{part} = \%_{os} \times Ws_s \quad (5)$$

Taking Sector 1 of the examples presented in Section 5.5, at day 10 we notice that S_{os} = 144 m^2 of this sector is occupied, representing $\%_{os}$ = 64% of this sector. However, for the entire floor, this occupancy represents $\%_{part}$ = 10.0% using the standard weights, or $\%_{parta}$ = 5.8% using the adjusted weights. Finally, the OR for a level is calculated by adding up all the relative occupancy rates ($\%_{part}$ or $\%_{parta}$) of all the sectors on the level. Thus, for this same example, with the adjusted weights, the floor is occupied at 40%.

4.4. Mini Artifact for Dynamic Representation

Figure 5 represents the standard mini artefact used to represent each OT on the DMORS. The upper part is used to represent the two (2) criteria [30]: (i) the internal location in the sector—whether the work is on the ground, the walls, or the ceiling and (ii) the internal movement—whether the work occupies the space in the area, or in a linear or punctual manner. The combination of these two (2) criteria provides nine (9) types of space occupancy, as shown in Figure 6. To make the interpretation easier, the internal location is represented by a trapezoid. So, if the trapezoid is on the side of the mini artifacts, it means that work is carried out on the walls. By the same logic, when the trapezoid is on the top it means that works is conducted on the ceiling, and when on the bottom it means that the OT is placed on the ground. As for the internal movements, these are represented by the shape of the background. A fully filled mini artefact represents an OT that will occupy a large surface area, a rectangle represents a linear OT, and a small square represents an isolated OT. Ardila and Francis [18] described the standard protocol that is used for the unique color and texture on the lower part of Figure 4 to help distinguish each OT on the DMORS.

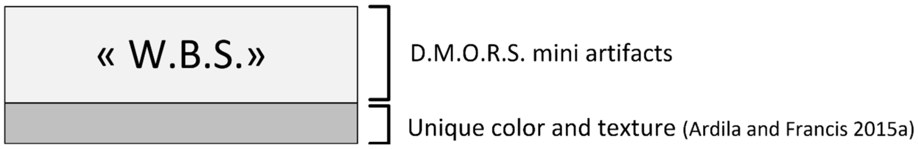

Figure 5. DMORS mini artifact legend [18].

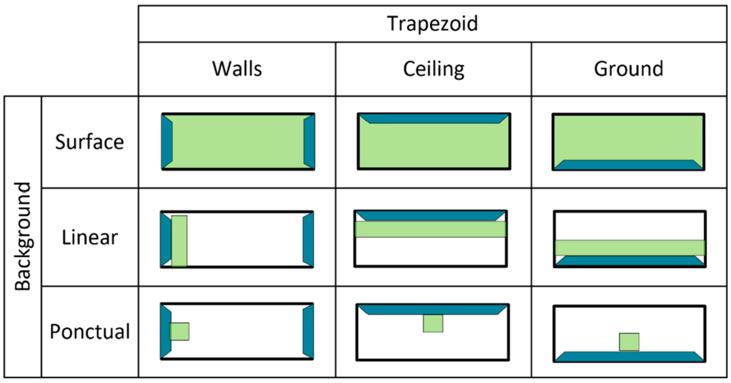

Figure 6. DMORS upper-part legend.

And, finally, as we discussed earlier in this paper, the final parameter to represent is the inclusivity (Figure 7), with plain light green representing an inclusive primary occupation, a green striped background used for secondary inclusive occupation, and plain dark green for an exclusive occupation.

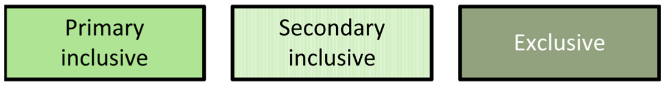

Figure 7. Mini artifact background legend.

5. The Creation of the DMORS and Validation

The case study presented in Figure 4 was used to test and validate the creation process presented in this paper. The interior of the fictitious building contains a total of 9 sectors. It was decided to focus on the interior finishing of the building, since, as the structure of the walls had just been installed, this usually represents the moment during construction when managing the available space and travel is the most important. Thus, the work presented will begin with the installation of the wiring and electrical boxes, followed by the installation of the gypsum panels, the joints, the painting, the electrical finish, the suspended ceiling and, finally, the finishing of the floors.

The process to prepare the DMORS, which is presented in Figure 8, is made up of five (5) major steps taking place in succession. First, the start date is selected, and the periods are covered in chronological order. Then, each of the levels available during this period is also covered in order. Thus, it is now possible to determine all the sectors that will be available on this level during this period and position the OT in every one of those sectors. The calculation process presented earlier in this article and the optimization process described in the following paragraph (Figure 9) are used to calculate the OR for each of the sectors present on this floor for this period. This leads, finally, to the calculation of the OR for the entire level and for the period.

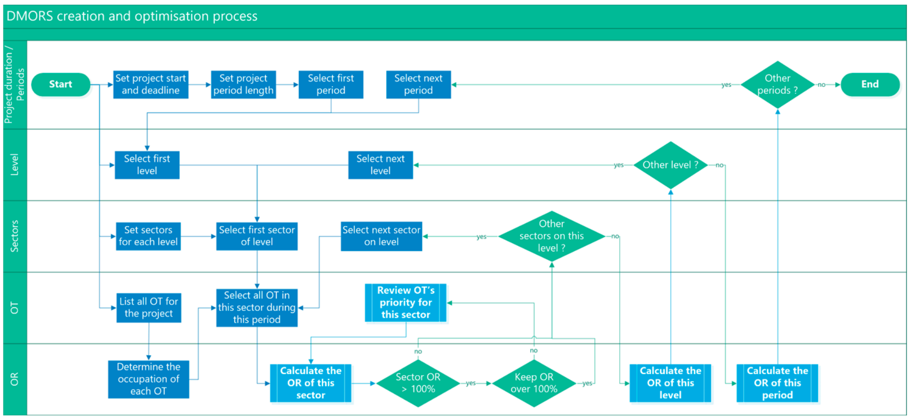

Figure 8. DMORS conceptual framework.

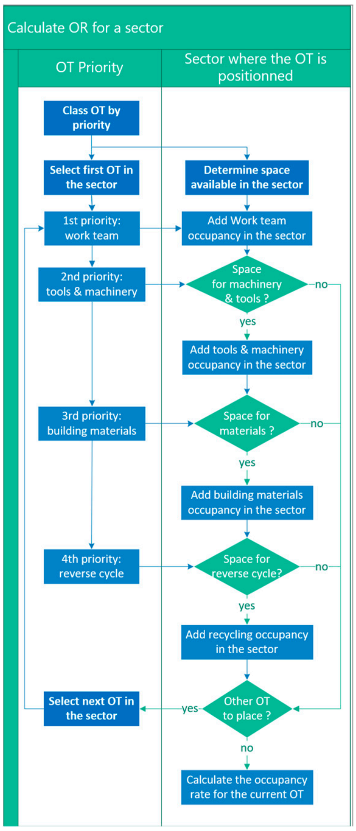

Figure 9. The OR calculations and optimization for a sector.

5.1. Project Duration and Periods

The primary goal of a schedule is to use the construction logic to determine the finish date of a project. So, knowing the starting date of the construction phase, the first piece of data that can be determined during the conception of the DMORS is the finish date of the construction. But since this is a fictitious case study, the project start date will be set to zero (0). Selecting the period length will depend on the control the project manager has on the project. But since it is a schedule designed for work coordination, we recommend using periods lasting between 1 day and 1 week. For the case study, each period will represent one (1) business day.

5.2. Sectors for Each Level

Starting from the architectural plans of the project, which are generally divided into floors, the project manager will then have to identify the sectors that will be present on each floor. A good starting point is to use the rooms on the floor, with the walls making good landmarks to identify the sectors. However, in the case of a very large room, it might be counterproductive to think of it as a single sector. In this case, the project manager might want to subdivide this large room into several smaller sectors. This will allow him to optimize the use of the available space in this large room. Subsequently, the inner perimeter of the walls and the available surface area, presented in Table 2, can be calculated directly on the plans.

5.3. OT

Determining all the OTs for the project will require a little more thought on the part of the project manager. The project responsibility matrix, with the WBS on one axis and the OBS on the other, could be a good starting point to identify all the work teams that will be needed throughout the project. Each of them can be represented by a distinctive OT. Each work team will generally need locations, tools, machinery, and materials, which will also be represented by distinctive OTs. The graphical representation (Section 4.4) can be applied for each of the OTs that will be shown on the schedule, which are summarized in Figure 10.

Occupation type	Description	Internal			Occupation	Units	Number of teams	Artifact
		Position	Movement	Inclusivity				
Work team	Electrical wiring installation	Wall	Linear	Primary inclusive	20	%	1	E.W.I.
Inbound Storage	Electrical storage	Floor	Surface	Secondary inclusive	2.00	m^2	N/A	E.S.
Work team	Gypsum board installation	Wall	Surface	Primary inclusive	3	m	2	G.I.
Inbound Storage	Gypsum board and plaster	Floor	Surface	Secondary inclusive	4.5	m^2	N/A	G.S.
Work team	Plaster and sanding	Wall	Suface	Exclusive	100	%	2	P.S.
Work team	Wall painting	Wall	Surface	Primary inclusive	3	m	1	W.P.
Work team	Ceeling electrical finition	Ceiling	Punctual	Secondary inclusive	50	%	2	C.E.F.
Inbound Storage	Ceeling light	Floor	Surface	Secondary inclusive	5	%	N/A	C.L.
Work team	Wall electrical finition	Wall	Punctual	Secondary inclusive	30	%	1	W.E.F.
Inbound Storage	Electrical finition	Floor	Surface	Secondary inclusive	2.00	m^2	N/A	E.F.
Work team	Suspended ceeling installation	Ceiling	Surface	Primary inclusive	100	%	2	S.C.
Inbound Storage	Suspended ceeling	Floor	Surface	Secondary inclusive	15	%	N/A	C.S.
Work team	Floor tiles installation	Floor	Surface	Exclusive	100	%	2	F.T.
Inbound Storage	Floor tiles storage	Floor	Surface	Secondary inclusive	4	m^2	N/A	F.T.S.
Outbound Storage	Recycling	Floor	Surface	Secondary inclusive	10	m^2	N/A	R.

Figure 10. OTs for the case study.

In order to better visualize the effect that each OT will have on the sectors, we start with their internal location and movement in each sector where the work will be performed. Subsequently, the inclusiveness of each OT will depend primarily on their priority during the construction process. As an example, it is important to complete the installation of electrical wiring before installing the gypsum panels on the walls. Thus, the installation of electrical wiring will be considered "primary inclusive". However, since the electrical finish usually takes up little space and can be easily postponed without negatively impacting the schedule, it is considered "secondary inclusive". And, because of the dust generated by the plaster and sanding, workers have to wear extra protective equipment to enter the sector. So, the task "plaster and sanding" is considered "exclusive". As for the "floor tiles installation", the processes require the floor to be properly cleaned before the installation, so this task is also considered "exclusive".

5.4. OR

To calculate the OR, first the occupation of each OT must be determined (Figure 10). There are three (3) ways to express the occupation of an OT: (i) in scare-meters (m^2), (ii) in meters (m), and (iii) in percentages (%). An occupation is expressed in scare-meters when the size of the OT can be directly used, such as for the 4 ft $\times$ 12 ft (1.2 m $\times$ 3.6 m) gypsum boards, which occupy around 4.5 m^2. But for other OTs, additional analysis will be required. The project manager will use an occupation expressed in meters (m) for linear work. So, to keep with the gypsum theme, to make sure the gypsum installation team has sufficient space to work, a distance along the inner perimeter of the walls must be reserved, like the 3 m proposed in the case study. Finaly, a percentage can be used if the occupation cannot be expressed in scare-meters or in meters. This can be seen, for example, in the electrical ceiling finishing, which will use about 50% of the available space, or the floor tile installation, that will use 100% of the available space. Then, the procedure in Figure 9 can be applied to calculate the OR of each sector and that in Section 4.3.4 to calculate the OR for the entire sector for each period.

5.5. DMORS Creation

The initial creation of the DMORS is mainly carried out using the same procedure as for chronographic modeling [19,31], and by applying the mini artifacts in Figure 10. This will generate the schedule presented in Figures 11 and 12. It will then be possible to display the occupancy that each OT will have in the area where they are positioned and to calculate and display the OR by period, for each sector, for each floor, and for the entire project, thus giving the schedule presented in Figure 13.

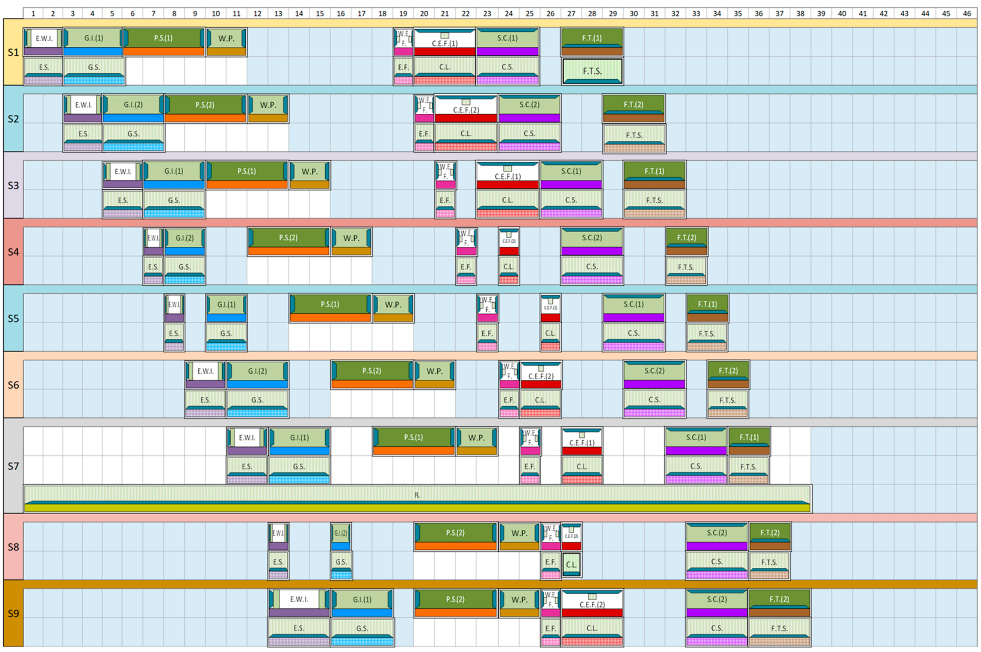

Figure 11. A chronographic modeling schedule for the case study.

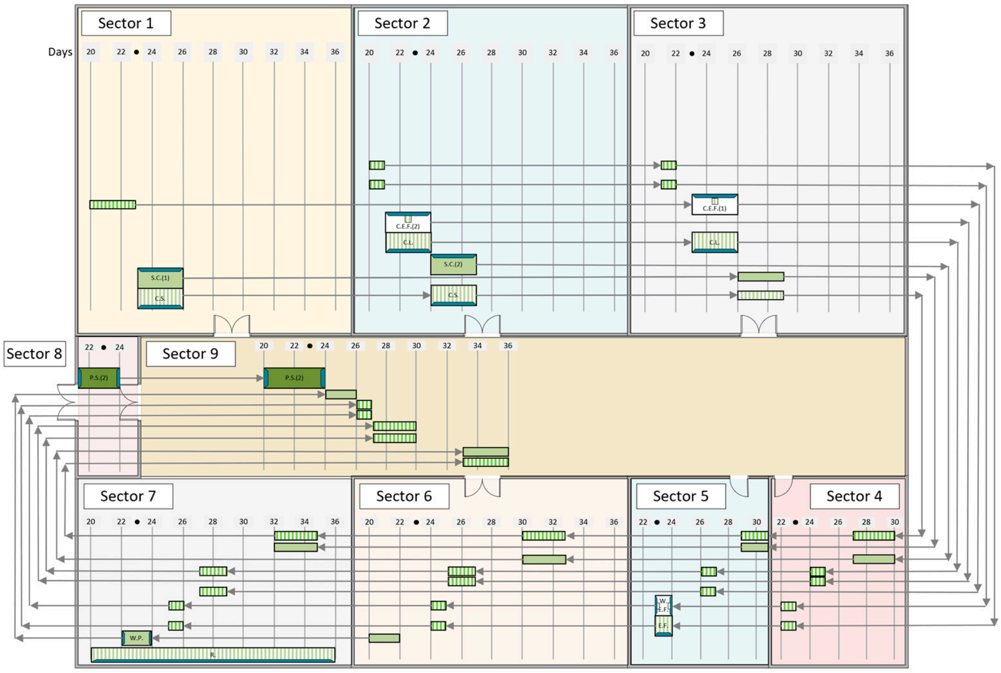

Figure 12. Site–spatial–temporal modeling for the case study.

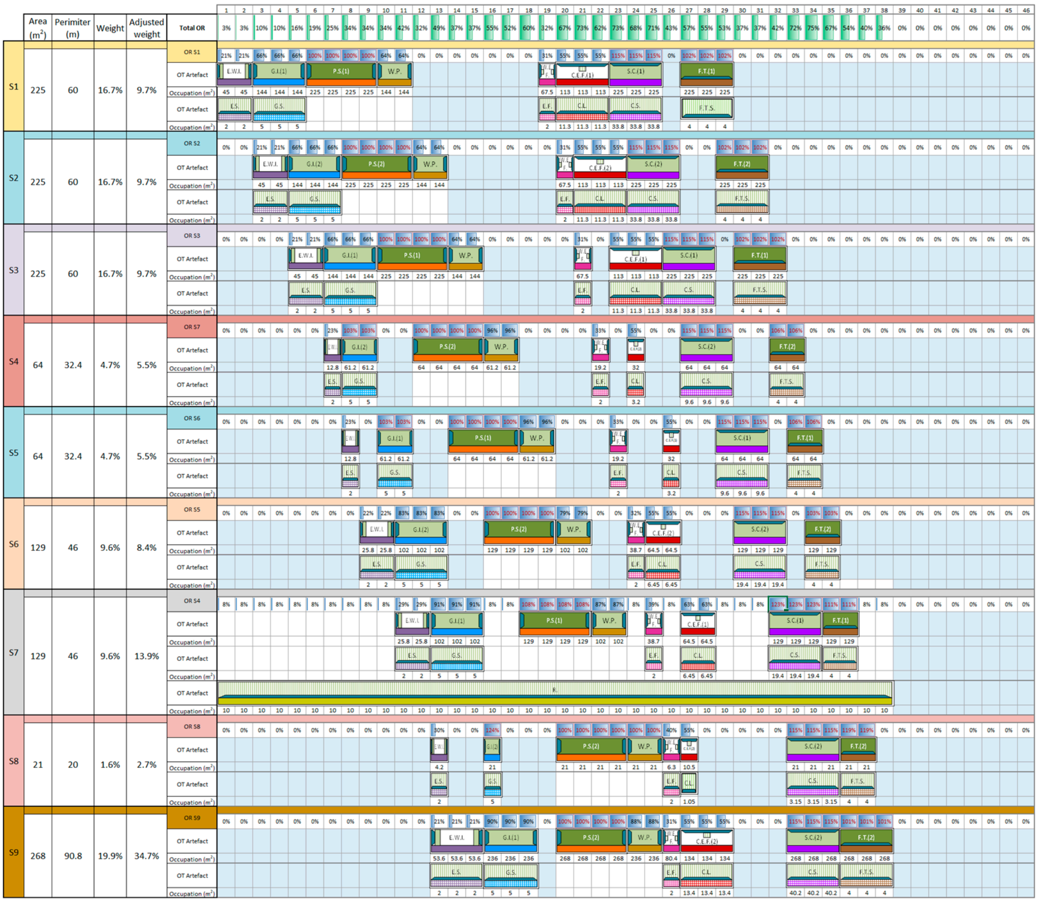

Figure 13. The DMORS for the case study using adjusted weight.

5.6. Optimization

For a given period, each sector of the project has a list of OTs that must be positioned. The manager must therefore prioritize the OTs present. The DMORS optimization process is based on two (2) elements: (i) the prioritization of the OTs present in a sector/period to calculate the OR (Figure 9) and (ii) what to do if a sector's OR is greater than 100%. Then, when calculating the OR for a sector, the OTs are positioned successively according to this prioritization by validating if there is enough space in the sector before positioning the next OT. In the event that there is not enough space to position an OT or the OR of the sector is greater than 100%, the manager will have to choose between leaving positioning as is and accepting that this sector will be overused or reviewing the prioritization of OTs and moving the lower priority OTs to another sector.

6. Discussion

The effective management of space in construction projects is critical to ensuring efficient workflows, reducing congestion, and optimizing resource allocation. This study introduced the Dynamic Model of the Occupancy Rate Schedule (DMORS), which brings together space planning principles and dynamic spatiotemporal modeling, to address limitations in traditional construction management tools. The DMORS offers project managers a novel means of scheduling that includes dynamic visual representations of space occupancy, providing an enhanced capability for predicting and optimizing space utilization during the planning phase.

This study's approach to space management aligns with the existing body of research that highlights the importance of spatiotemporal planning in construction. Like the work of [5], which underscored the need for collecting and utilizing spatiotemporal data from subcontractors for more effective planning, the DMORS integrates both spatial and temporal dimensions into the scheduling process. However, the DMORS goes beyond the static or manual approaches discussed in earlier works by incorporating real-time adjustments to space occupancy rates, offering a more dynamic and flexible solution than prior models such as PECASO by Mallasi [7], which focused primarily on minimizing conflicts through static workspace competition analysis.

A key contribution of the DMORS is its emphasis on the occupancy rate (OR) as a critical metric for managing construction sites. This concept shares similarities with the occupancy-based frameworks proposed by Guo [6] and Said and El-Rayes [10], which also sought to resolve space conflicts. However, while those models relied heavily on deterministic and heuristic methods and pre-calculated values, the DMORS introduces a dynamic calculation methodology that is adaptable to ongoing changes on the construction site. This flexibility addresses one of the major limitations found in previous models, which often struggled with the adaptability required in highly dynamic construction environments.

The integration of graphical elements into the DMORS for visualizing space usage at different points in time is another area where this study diverges from previous work. The graphical modeling techniques employed in the DMORS build upon concepts from chronographic modeling [19,25–27], but with additional features such as mini artifacts that allow for more precise visual tracking of space usage. Unlike the more rigid visualizations in 4D-BIM models discussed by Mirzaei et al. [12], the DMORS provides a more flexible and easily interpretable visual representation of both space and time, thus making it more accessible for project managers to optimize their workflows.

Moreover, while previous models like the Location-Based Management System (LBMS) focused on ensuring continuous workflows through linear planning [13–15], the DMORS focuses on building projects where linear planning is almost impossible to apply and adds an additional layer by considering space as a critical resource that must be dynamically managed alongside time and labor. This offers a more comprehensive approach to project management, especially in environments with constrained resources or overlapping activities.

7. Conclusions

This paper has demonstrated the development of a construction planning system that integrates chronographic modeling with the dynamic calculation of the occupancy rate (OR) on construction sites. By combining spatial visualization and dynamic planning, this system allows construction managers to better anticipate space utilization, minimize travel, and improve overall safety and efficiency.

So, this study has introduced the Dynamic Model of the Occupancy Rate Schedule (DMORS), which enables managers to visualize and dynamically adjust the occupation of space on a site. By calculating ORs for individual sectors and entire floors, the model allows for an optimized workflow that minimizes overcrowding and maximizes the effective use of available space. The validation of static artifacts and the DMORS through a case study has provided a proof of concept, highlighting the model's potential to optimize construction planning.

The process begins by dividing the site into sectors to calculate available surface areas and the perimeter wall length for each sector. To determine the OR for an entire floor, the relative weight of each sector is calculated. Since some sectors are more critical than others during construction, adjusted weights are also applied.

Next, the total occupied area of a sector is calculated by summing the space used by all OTs within that sector. This spatial positioning allows for a static and dynamic representation of the OR for each sector, floor, and timeframe within the project's schedule (DMORS).

To provide a dynamic visualization, mini artifacts have been designed to indicate the positioning of OTs in both space and time, along with their interrelationships. A procedure was presented that enables dynamic spatiotemporal representation and optimization of ORs. The proposed framework was tested using a fictitious project to demonstrate the effectiveness of this visualization and optimization process.

Despite the promising results, several constraints and limitations must be addressed in future research. The proposed system requires constant data collection and processing, which necessitates the development of specific software applications. Furthermore, the need for continuous updates and tracking of changes during construction is critical to ensuring the model's accuracy in real-time scenarios. Future validations on real construction projects will be essential to fully assess the practicality and efficiency of the DMORS system in optimizing space usage on active job sites.

Overall, the proposed construction planning system represents a step forward in dynamic space management, and its integration into construction workflows holds good potential for improving project planning, enhancing safety, and streamlining the use of resources on complex construction sites.

8. List of Symbols

8.1. The Building and the Sectors

- Area occupied in a sector.
- $\%_{os}$ = percentage occupied in a sector.
- S_m = maximum area available in a sector.
- If_s = sector importance factor.
- Ws_s = weight of the sector.
- Wsa_s = adjusted sector weight.

8.2. Types of Occupations

- S_{ot} = area occupied by the type of occupation.
- $\%_{part}$ = occupancy rate of a part of the site.
- $\%_{parta}$ = adjusted occupancy rate of a part of the site.

Author Contributions: Writing—original draft, S.M.-P.; writing—review and editing, A.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data that support this study's results are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors confirm they are the sole contributors to this work and have approved it for publication. The authors declare no conflicts of interest.

References

1. Riley, D.R. Sanvido VEPatterns of Construction-Space Use in Multistory Buildings. *J. Constr. Eng. Manag.* **1995**, *121*, 464–473. [CrossRef]
2. Riley, D.R. Sanvido VESpace planning method for multistory building construction. *J. Constr. Eng. Manag.* **1997**, *123*, 171–180. [CrossRef]
3. Thabet, W.Y. A Space-Constrained Resource-Constrained Scheduling System for Multi-Story Buildings. Ph.D. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, 1992.
4. Thabet, W.Y. Beliveau, Y.J. SCaRC: Space-constrained resource-constrained scheduling, system. *J. Comput. Civ. Eng.* **1997**, *11*, 48–59. [CrossRef]
5. Akinci, B.; Fischer, M. An Automated Approach for Accounting for Spaces Required by Construction Activities. In Proceedings of the Construction Congress VI, Orlando, Florida, USA, 20–22 February 2000; pp. 1–10.
6. Guo, S.-J. Identification Resolution of Work Space Conflicts in Building Construction. *J. Constr. Eng. Manag.* **2002**, *128*, 287–295. [CrossRef]
7. Mallasi, Z. Dynamic quantification analysis of the construction workspace congestion utilising 4D visualisation. *Autom. Constr.* **2006**, *15*, 640–655. [CrossRef]
8. Chua, D.K.H.; Yeoh, K.W.; Song, Y. Quantification of Spatial Temporal Congestion in Four-Dimensional Computer-Aided Design. *J. Constr. Eng. Manage.* **2010**, *136*, 641–649. [CrossRef]
9. Bansal, V.K. Use of GIS and Topology in the Identification and Resolution of Space Conflicts. *J. Comput. Civ. Eng.* **2011**, *25*, 159–171. [CrossRef]
10. Said, H.; El-Rayes, K. Optimal utilization of interior building spaces for material procurement and storage in congested construction sites. *Autom. Constr.* **2013**, *31*, 292–306. [CrossRef]
11. Said, H.; Lucko, G. Float Types in Construction Spatial Scheduling. *J. Constr. Eng. Manag.* **2016**, *142*, 04016077. [CrossRef]
12. Mirzaei, A.; Nasirzadeh, F.; Parchami Jalal, M.; Zamani, Y. 4D-BIM Dynamic Time–Space Conflict Detection and Quantification System for Building Construction Projects. *J. Constr. Eng. Manag.* **2018**, *144*, 04018056. [CrossRef]
13. Kenley, R.; Seppänen, O. *Location-Based Management for Construction: Planning, Scheduling and Control*; Taylor & Francis: Hoboken, NJ, USA, 2010.
14. Kenley, R.; Seppänen, O. Location-based management of construction projects: Part of a new typology for project scheduling methodologies. In Proceedings of the 2009 Winter Simulation Conference (WSC), Austin, TX, USA, 13–16 December 2009; pp. 2563–2570.
15. Olivieri, H.; Seppänen, O.; Denis Granja, A. Improving workflow and resource usage in construction schedules through location-based management system (LBMS). *Constr. Manag. Econ.* **2018**, *36*, 109–124. [CrossRef]
16. Francis, A.; Miresco, E. A chronographic method for construction project planning. *Can. J. Civ. Eng.* **2006**, *33*, 1547–1557. [CrossRef]
17. Ardila, F.A.; Francis, A. The chronographic protocol: Validation of textures and colors. *Int. J. Innov. Technol. Explor. Engireering* **2015**, *5*, 8.
18. Ardila, F.A.; Francis, A. Design and Validation of the First Phase of the New Chronographical Standard Protocol for Construction Project Scheduling. In Proceedings of the 5th International/11thConstruction Specialty Conference, Vancouver, BC, Canada, 7–10 June 2015; Volume 104, pp. 1–9.
19. Francis, A. The chronographical approach for construction project modelling. *Proc. Inst. Civ. Eng. Manag. Procure. Law.* **2013**, *166*, 188–204. [CrossRef]
20. Francis, A.; Morin-Pepin, S. The Concept of Float Calculation Based on the Site Occupation using the Chronographical Logic. *Procedia Eng.* **2017**, *196*, 690–697. [CrossRef]
21. Weaver, P. Henry L Gantt, 1861–1919 Debunking the myths, a retrospective view of his work. *PM World. J.* **2012**, 1–17.
22. Gantt, H.L. Work, wages, and profits. *New York the Engineering Magazine*, 1919; p. 336.
23. Frandson, A.; Berghede, K.; Tommelein, I.D. Takt time planning for construction of exterior cladding. In Proceedings of the 21st Annual Conference of the International Group for Lean Construction, Fortaleza, Brazil, 29 July–2 August 2013; pp. 527–536.
24. Frandson, A.; Tommelein, I.D. Development of a takt-time plan: A case study. In Proceedings of the 2014 Construction Research Congress, Atlanta, GA, USA, 19–21 May 2014; pp. 1646–1655.
25. Francis, A. La Modélisation Chronographique de la Planification des Projets de Construction. Ph.D. Thesis, École de Technologie Supérieure, Montreal, QC, Canada, 2004.
26. Francis, A. Chronographical spatiotemporal scheduling optimization for building projects. *Front. Built Environ.* **2019**, *5*, 1–14. [CrossRef]
27. Francis, A. Chronographical Site-Spatial-Temporal Modeling of Construction Operations. *Front. Built Environ.* **2020**, *6*, 67. [CrossRef]
28. Morin-Pépin, S.; Francis, A. Modeling and categorizing standardized artifacts for scheduling occupancy on building construction sites. *Front. Built Environ.* **2024**, *10*, 1380106. [CrossRef]

29. Hevner, A.R.; March, S.T.; Park, J.; Ram, S. Design science in information systems research. *MIS Q. Manag. Inf. Syst.* **2004**, *28*, 75–105. [CrossRef]
30. Morin-Pépin, S.; Francis, A. Technologies currently available to obtain the occupancy rate of ressources on a construction sites. In Proceedings of the 7th CSCE Annual Conference, Montreal, QC, Canada, 12–15 June 2019; Volume 9.
31. Francis, A. Applying the chronographical approach for modelling to different types of projects. In Proceedings of the 5th International/11th Construction Specialty Conference, Vancouver, BC, Canada, 7–10 June 2015; pp. 1–9.