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Spatiotemporal chronographical modeling of procurement and material flow for building projects

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Abstract. Planning and management building projects should tackle the coordination of works and the management of limited spaces, traffic and supplies. Activities cannot be performed without the resources available and resources cannot be used beyond the capacity of workplaces. Otherwise, workspace congestion will negatively affect the flow of works. Better on-site management allows for substantial productivity improvements and cost savings. The procurement system should be able to manage a wider variety of materials and products of the required quality in order to have less stock, in less time, using less space, with less investment and avoiding multiple storage stations. The objective of this paper is to demonstrate the advantages of using the Chronographic modeling, by combining spatiotemporal technical scheduling with the 4D simulations, the Last Planner System and the Takt-time when modeling the construction of building projects. This paper work toward the aforementioned goal by examining the impact that material flow has on site occupancy. The proposed spatiotemporal model promotes efficient site use, defines optimal site-occupancy and workforce-rotation rates, minimizes intermediate stocks, and ensures a suitable procurement process. This paper study the material flow on the site and consider horizontal and vertical paths, traffic flows and appropriate means of transportation to ensure fluidity and safety. This paper contributes to the existing body of knowledge by linking execution and supply to the spatial and temporal aspects. The methodology compare the performance and procurement processes for the proposed Chronographic model with the Gantt-Precedence diagram. Two examples are presented to demonstrate the benefits of the proposed model and to validate the related concepts. This validation is designed to test the model's graphical ability to simulate construction and procurement.

Keywords: building; chronographic; management; modelling; precedence diagram; procurement; project; scheduling; space planning

1. Introduction and literature review

The planning and management of building projects should include the coordination of works and the management of limited spaces, traffic and supplies. Such activities cannot be performed without the necessary resources. These resources also cannot extend beyond workplaces' capacity, or else workspace congestion will negatively affect workflow. During the execution process, the

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space requirements of site processes, circulation and intermediate storage vary depending on the type of operation. The objectives of this paper are to study on-site material flow and to consider various methods (horizontal and vertical paths, traffic flows and appropriate means of transportation) for ensuring fluidity and safety. The procurement system should be able to manage a wide variety of materials and products, as well as meet the required quality standards, in order to reduce stock, time, space and investment requirements and without a need for multiple storage stations.

1.1 Procurement strategies

A good procurement strategy ensures smooth takt production and minimizes waiting time (e.g., laborers waiting for materials or materials waiting for laborers). The application of lean principles in the procurement process and in material-flow management could help to reduce or even eliminate waste. Lean manufacturing theories include seven categories of waste: transportation, inventory, motion, waiting, overprocessing, overproduction and defects. Lean manufacturing is aimed at identifying and eliminating all sources of waste, especially non-value-added activities (Muda), overexploitation of machines and labor (Muri) and inequalities in the rate of production (Mura).

Bertelsen and Nielsen (1997) discussed various procurement strategies such as i) pushed flows, a logistical system that involves planning without regard to the actual need; ii) the pull system, a logistical system based on production need; and iii) just-in-time (JIT), which minimizes stock in each stage of production.

With the pushed-flows strategy, materials and equipment are supplied early in the process. This can affect the capital and cause a lack of liquidity, as interest incurred on excess inventory is an unnecessary expense and as additional storage generates excess costs. Materials can also deteriorate or be stolen during the storage period unless special care is taken. For example, electrical equipment often has to be stored in enclosed spaces to prevent damage. Intermediate stock also occupies space, which can prevent construction operations and affect critical space calculations. The existence of intermediate stocks is thus considered wasteful.

The JIT and pull systems are based on the idea that intermediate stock has no value and is therefore wasteful. JIT is also called the “5 zeros” system, referring to zero failure, zero delay, zero paper, zero inventory and zero defects. The difference between the pull and JIT systems is that the pull system involves minimal stock, whereas the JIT system requires no stock at all. In the pull system, an inventory threshold (based on the production threshold) is used to determine when an item needs to be reordered. Using the JIT system or the pull system is more economical but riskier than using the pushed-flow system.

Eliminating waste does not mean operating on a JIT basis at all times; in fact, this can hardly be achieved on building sites. Eliminating waste helps to limit losses due to unforeseen events. In addition, human beings are not robots, so some error should be tolerated. To account for these variables, planners should consider temporal, inventory and capacity buffers (which work similarly to cost contingencies). Buffers reduce risk and increase schedule stability; they are planned and controlled. Waste, by contrast, indicates a lack of planning and control.

1.2 Inventory management and conflict detection

Several techniques can be used for inventory management. According to Ala-Risku and Karkkainen (2006), a site can employ an integrated system, in which the materials required for each task are recorded in a list. This task list can be linked to a list of materials. As a result, the system can identify the tasks for which the material constraints are not yet met and delay them. These databases also enable users to establish the location of the various materials that are needed for a task, the materials that are present at any given location, and the lengths of time that given materials have been kept in their current locations. However, such systems must be linked to project schedules, which makes their implementation complex and requires considerable effort. Experience shows that this type of system is much more likely to fail than other types of systems based on Lean.

Bertelsen and Nielsen (1997) proposed a combination approach involving both global logistics planning and JIT. In this method, for each operation, the details of the necessary materials are bundled in units based on the day that they will be delivered (an idea inspired by Ikea's system). Purchase orders, which are grouped using a rolling three-week period, are sent to suppliers. The orders for the coming week are purchased, and those for the following two weeks are provided to allow suppliers to anticipate future orders and coordinate with the project's needs. However, this method is complex and requires perfect coordination between all stakeholders, which is quite difficult to achieve.

Given the difficulty of ensuring effective spatial management of stock, many researchers have attempted to develop software that can use complex algorithms to determine optimal organization based on various parameters. The typical selection criteria for these algorithms are distance or the cost associated with transit within the site, both of which should be minimized. However, these objectives are difficult to model mathematically (Thomas *et al.* 2005). The critical space analysis approach links the spatial and temporal aspects of a project, allowing for a space to be associated to a task by checking for the existence of conflicts at the site between the critical planning path and the organization's critical space (Winch and North 2006). Researchers have developed numerous algorithms for the spatial and temporal organization of sites. These algorithms usually are complex because they consider all the existing variables. Given the magnitude of this task, these algorithms are only effective in certain cases, as they are based on reductive assumptions and require that the project unfold without any unforeseen elements.

To manage storage, Zouein and Tommelein (2001) defined four storage-space profiles according to current and future space needs. Su and Cai (2014) presented a method based on the life cycle of building spaces. Thus, during the execution process, space requirements may vary depending on the type of operation. Riley and Sanvido (1997) proposed a methodology for identifying the required space for each activity, including conflict detection through the superposition of work sequences for activities occurring at the same time. Zouein and Tommelein (2001) used a similar but partially automated system, which enables users to discretize the duration of the project into time intervals based on the arrival and departure of resources.

Winch and North (2006) proposed software that would calculate a ratio of workspace congestion based on the allocated resources. For each space, the software would calculate this ratio and then alert managers of any congestion using a color-coded system with three cases: overloaded, underused or optimized. Chavada *et al.* (2012) also detailed the detection of space and congestion conflicts, which are often caused by overlapping activities in the same workspace. Specifically, Chavada *et al.* proposed geometric detection by means of an intersection test that compares the minimum and maximum values for the zone boundaries in each of the Cartesian dimensions (X, Y and Z). Su *et al.* (2012) proposed automatic conflict detection using a system in which all points that belong to an object are listed in a data center; activities are then related to the objects, and when two activities are active, their positions are compared to identify conflicts.

Pheng and Chuan (2001) described a method that contractors can use to manage storage space using six options: i) appropriate allocation of storage space, ii) adaptive stacking to artificially increase storage space, iii) use of alternative storage methods (e.g., racks), iv) rental of additional space, v) improvements in coordination with suppliers, and vi) regular cleaning of on-site storage spaces. Pheng and Chuan also stated that algorithms are unsuited to the real problems in the construction sector. According to Ala-Risku and Karkkainen (2006), solutions must be easy and quick to enact, efficient and inexpensive. Innovative management techniques can be used to improve this situation (Bell and Stukhart 1987). Site development is complex partly because a development that is relevant at the beginning of the project may no longer be suitable by the end (or even the middle) of the project. By observing several projects, researchers have identified some basic rules (Thomas *et al.* 2005). Obviously, no solution is ideal for all scenarios, but it is conceivable to combine several solutions in order to gain the advantages of each. For example, visual systems with simple signals (e.g., color cards) could be used to indicate a site's material needs for the next few days (or weeks), and a system could be used to automatically trace materials using barcodes, RFID tags or GPS.

Lean principles can also be used to manage inventory in the pull-flow system. The use of space planning and the kanban system can help to control inventory, determine the location of items and keep the site clean. Workers in this system are responsible for reporting their short-term needs using various products. These needs are coordinated during site meetings so as to control both the supply and the level of the intermediate storage.

1.3 Intermediate stocks and site-space management

Better on-site management allows for substantial productivity improvements and cost savings (Ng *et al*. 2009). The presence of inventory hinders performance by slowing problem detection, preventing rapid reconfiguration, and creating both inventory and capital costs (Horman and Thomas 2005). Thus, an optimized construction-site layout improves productivity and ensures that safety standards are met (Ning, Lam and Lam 2010). In construction projects, spatial scheduling of tasks and organizing temporary installations have to be considered as part of the site layout (Winch and North 2006). Because on-site storage space is limited, material management of storage capacity must be optimized by providing a minimum and preventing stock-outs. The use of 4D simulations is a good solution, as they combine site management and site scheduling. For a project in Chile, Rischmoller *et al*. (2001) used a system that combined a 3D model with a critical path. After completing the project, the entire planning team was convinced that this 4D system was effective, as it allowed for the visualization of alternatives that would have been impossible to envision without this system.

Currently, 4D simulations combine 3D models either with a linear schedule or with Gantt-Precedence diagrams (also called "precedence diagrams"). Each method has its limits.

The use of linear schedules helps address conflicts in a given physical location, thus preventing overlaps and congestion. However, this strategy does not ensure that the teams use certain areas continuously.

The Gantt-Precedence diagrams for schedule construction projects are widely known but have many shortcomings, especially with regard to the negative impact of the reverse critical path, the erroneous calculations that occur when using lags to simulate production and the use of time as the only constraint between activities. In addition, the use of multiple calendars affects scheduling calculations. The graphical rendering of schedules in Gantt-Precedence diagrams also leaves much to be desired. Fisk (2013) stated that, for medium and large projects, schedules often are difficult to present, follow and update. The extensive use of activities and constraints makes it difficult to read the diagrams' dependence lines, which are often very dense and which intersect with the activity lines. In addition, this method fails to help users detect and avoid conflicting activities in the various zones. User satisfaction also remains debatable. However, managers and planners typically have little choice in the matter, as the majority of scheduling software models only use this method.

Scholars have developed many solutions to address these methods' limitations: the Chronographic point-to-point relations, probabilistic dependencies and functions, modeling of work uncertainties, and evaluation of working areas' impact on margin calculations (Francis and Miresco 2000, 2006, Francis *et al.* 2013, Francis 2017). The schedule logic indicates the relational constraints and dependencies among physical entities (e.g., activities or resources). Chronographic modeling allows for the scheduling of projects using internal divisions, relationships, constraints, continuous functions, production probabilities and decisions (Francis and Miresco 2006, Francis *et al.* 2013). However, with these strategies, it is particularly difficult to simultaneously address spatial conflicts and ensure continuous team workflow. In addition, ensure accuracy, schedules must be highly detailed, which increases the required effort and reduces the visual clarity of the schedule graph. This method is the only way to produce a thorough model, however; a model with less detail would be only an approximation.

Moreover, subcontractors perform most activities in building projects. In this context, the project schedule should focus on site coordination and on workspace and traffic management. Despite this, this method focuses on defining activities and constraints (e.g., allocating and optimizing resources) based only on time. The Gantt-Precedence diagram method neglects several aspects related to working areas, circulation and material-flow management; it also only considers resources as attributes of activities. This method neglects construction-site management, which wastes time and money because of site congestion and wait times or, conversely, because of overly relaxed sites.

By linking spatial and temporal production, the Chronographic modeling uses sites' occupancy rates to calculate critical space flows and each project's optimal duration (Francis 2004, 2013, 2016, Francis and Morin 2017). This approach aims to improve sites by relaxing congested zones or by speeding up production. It focuses on optimizing the use of space, verifying site conflicts and ensuring ideal crew rotation.

Researchers have developed several lean methods to stabilize work on building sites. Examples include space planning, takt planning, visual management and the Last Planner System. Frandson and Tommelein (2014) used a Takt-time planning to stabilize the frequency of teams' rotation between zones.

Visual communication can also be improved through layering, sheeting, juxtaposition, alteration and permutation; this allows for better groupings, hierarchies and classifications of project information (Francis 2013). Graphical modeling is a suitable tool for presenting project information, as it allows for the communication of the greatest amount of data in the shortest time while using the fewest words and the smallest area (Tufte 1983). Although readers understand text sequentially, they understand graphs globally, which allows them to view the leaves and branches at the same time that they see the whole tree, so to speak (Bertin 2005). Graphs also provide better results than text when automatic algorithms fail (Keim 2002).

The emergence of new technologies especially those related to BIM and 4D through 7D simulations has affected project-management methods and led to major changes in how projects are managed, coordinated, modeled and planned. New technologies have also changed how information is communicated. In scheduling, the traditional Gantt-Precedence-diagram-based scheduling method is poorly suited to this new reality, as managers must adapt to a variety of project types and problems. Thus, an optimal solution would be a graphical method that can, first, model project operations and information using various compatible facets and, second, schedule various project types. Thus, the efficient use of 4D simulations by combining spatiotemporal technical scheduling with the logic of the Last Planner System offers a real advantage.

2. Research goals, objectives and methodology

The main goal of this research is to model a procurement process the enables the management of a wide variety of materials and products so as to reduce stock, time, space and investment requirements while avoiding the need for multiple storage stations. To optimize the execution process and to ensure fluidity and safety, the system should ensure smooth takt production.

This paper will work toward the aforementioned goal by examining the impact that material flow has on site occupancy. Material flow includes horizontal and vertical paths, traffic flows, and appropriate means of transportation to ensure fluidity and safety (Francis *et al*. 2018). Procurement strategies must also minimize the movement of materials and provide appropriate means of transport so as to ensure fluidity and safety while minimizing intermediate stock. Fluidity in the transmission of information facilitates the implementation of such strategies. A procurement strategy should also ensure smooth takt production and minimize all types waiting (e.g., laborers waiting for materials or materials waiting for laborers).

This paper contributes to the existing body of knowledge by linking execution and supply to the spatial and temporal aspects. This link facilitates a continuity of spatial use by maximizing a site's occupancy rate. It also promotes an appropriate rotation of labor and materials in the various areas of the site. The main advantage of the proposed method is its simplicity, which was possible due to the proposed graphical model's ability to communicate information clearly, to facilitate collaboration and to optimize procurement and execution at the construction site. This was also enabled by the use of the Last Planner System, which involves all those who are responsible for on-site execution and decisions.

The objective of this paper is to demonstrate the advantages of using the Chronographic modeling, the Takt-time and the Last Planner System when modeling the construction of building projects. The proposed spatiotemporal model promotes efficient site use, defines optimal site-occupancy and workforce-rotation rates, minimizes intermediate stocks, and ensures a suitable procurement process.

This study's methodology includes a review of the literature on procurement and stock management for building sites. In addition, the performance and procurement processes are compared for the proposed Chronographic model and the Gantt-Precedence diagram. Finally, two examples are presented to demonstrate the benefits of the proposed model and to validate the related concepts. This validation is designed to test the model's graphical ability to simulate construction and procurement.

3. Comparison between the Gantt-Precedence diagram and the Chronographic model

3.1. An example of scheduling using a Gantt-Precedence diagram

The following example demonstrates the Gantt-Precedence-diagram scheduling of a floor that is repeated within a building. This scheduling example concerns the installation of building systems such as ventilation and heating, plumbing, fire protection, electricity, and communications; the erection of partition walls; the finishing work, including doors and windows, painting, flooring, carpentry and cabinetry; and the installation of an elevator. Figure 1 shows this schedule.

Traditional procurement methods are generally based on the progress of the schedule. The approval and manufacturing processes are tracked independently using tables. Finally, site's superintendent manages the on-site inventory through coordination with subcontractors. Given the quality of the obtained schedule, this task is quite difficult to achieve. Conflicts between work teams are quite common. The following subsections compare the modeling of an example using the Chronographic approach and using a Gantt-Precedence diagram.

3.2. Chronographıc modeling

Riley and Sanvido (1995) stated that project managers often underuse architectural and engineering plans and propose a generic method for describing spaces in multistory building projects. Riley and Sanvido's method identifies three kinds of spaces in a hierarchy (free, occupied by construction and occupied by products) as well as twelve types of spaces that are dedicated to processes (e.g., areas for unloading, transit, storage, prefabrication and work). In 1997, the same authors used colors and textures to better identify and model spaces (Riley and Sanvido 1997). Zouein and Tommelein (2001) later proposed similar methods.

Chronographic modeling (Francis 2013, 2016) uses an alternative concept for planning and scheduling spaces. This modeling layout's user interface is in the spatial dimension and is based on suitable visual parameters and their associated values. The result that a given project schedule can be visualized using numerous compatible approaches. For instance, the organizational approach permits alternation among visual approaches via the manipulation of graphics based on a set of defined graphical parameters.

Chronographic modeling is a hybrid approach that uses several strategies to model information, including various groupings and space planning. The Chronographic model defines the duration of the project according to the site's occupancy rate. The critical path is defined as the longest succession of critical areas; it is not based on critical activities. Thus, when zones are used for storage, this can affect those zones' critical paths. Minimizing storage is thus necessary when these areas are partially or fully critical. The cost of storage in a zone must be defined in terms of a daily rental cost. This cost must also include indirect expenses related to the resulting delays. Each zone thus has its own daily cost that is based on its level of criticality during a given period. Thus, this cost must be considered during stock management. The 3D BIM model can easily feed spatiotemporal scheduling with material quantities. The time aspect is used to define the quantities that are both currently in use on the site and planned for the coming weeks. The temporal aspect serves to create a compromise between work zones and storage areas. Finally, 4D simulations demonstrate how the dynamic evolution of work and storage areas can be used to determine the optimal duration and cost of execution.

The conceptual framework of the Chronographic modeling is based on a new protocol that organizes all of the elements that are required to perform the construction operation (both processes and models for logic, association and organization). This conceptual framework defines physical entities, which in turn represent each component that is required to perform construction operations: a) work, b) resources and c) locations. Physical entities are arranged graphically using

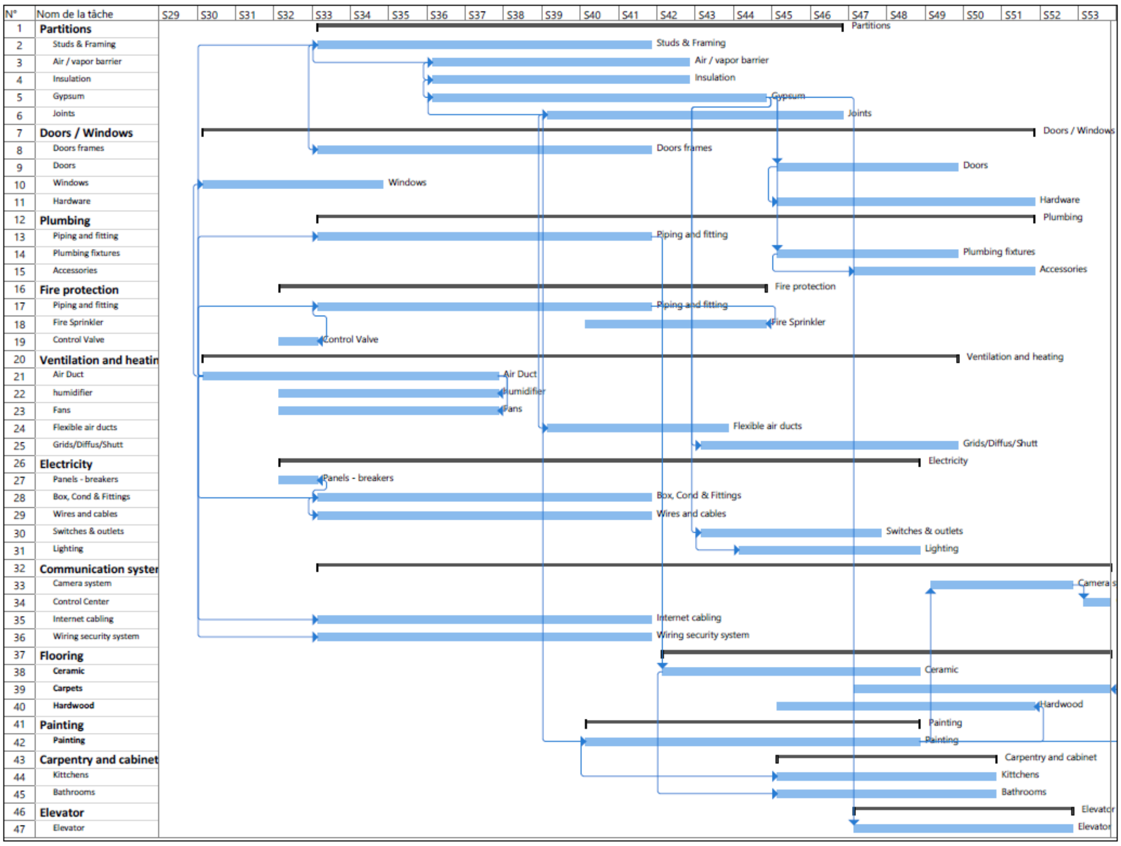


Fig. 1 Gantt-Precedence diagram scheduling for a building floor

various organizational means: distinction (e.g., layering and sheeting), association (e.g., hierarchy and grouping), external and internal scales (e.g., time, costs and work progress), and attributes that assign one type of physical entity to another (e.g., assigning activity to various locations or permanent materials to activities). For further explanation, please see Francis (2013) and Francis (2016).

3.3. The Chronographic modeling protocol

In the Chronographic method, the author analyzes the graphical modeling parameters for a construction project's scheduling and then proposes a standard chronographic protocol. The author studies the suitable visual parameters and their associated values in order to define the standard graphical presentation using shapes, sketches, codes, text, textures and colors.

This protocol is intended, first, to overcome difficulties related to the graphical visualization of the considerable amount of data that is needed for effective planning and, second, to increase the effectiveness of visual research based on humans' visual habits (Francis 2016). Figure 2 demonstrates the graphical protocol that is used in the Chronographic modeling:

1. Activities emplacement shows whether an activity concerns the ceiling, the walls, the floor or a combination. This graphical protocol uses rectangular borders.

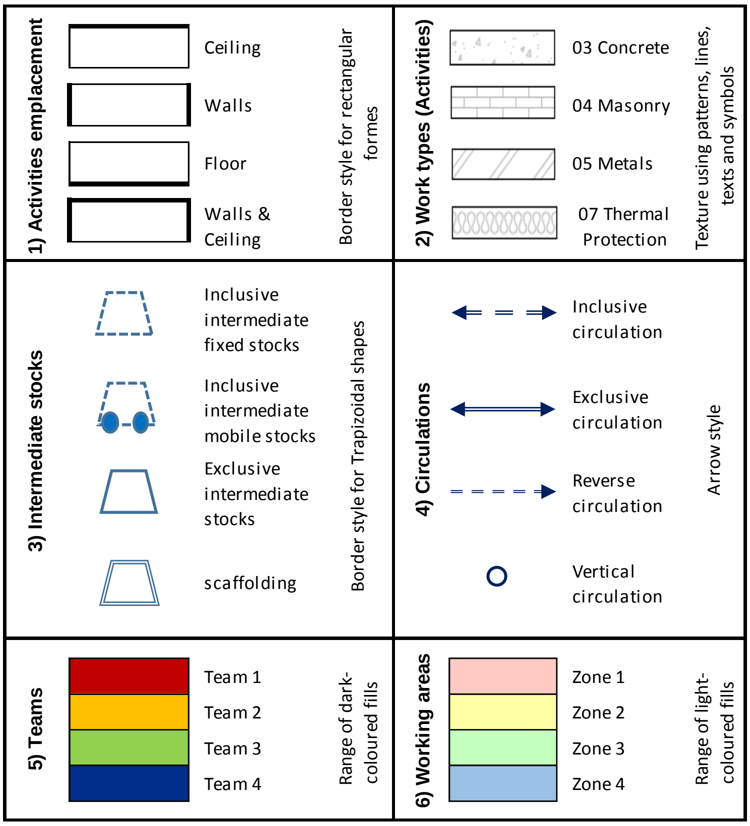
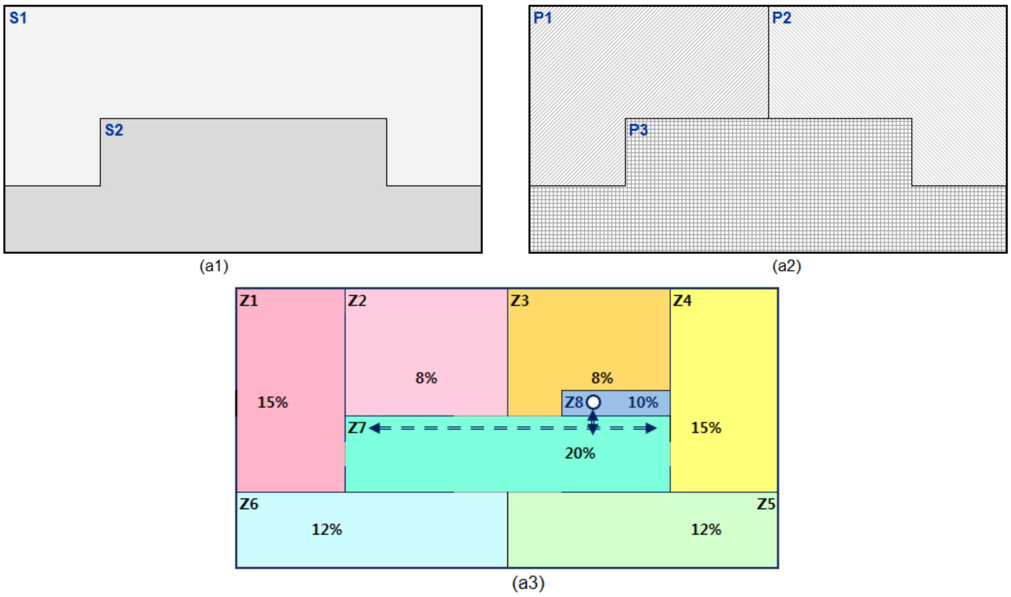


Fig. 2 The Chronographic protocol extract from Francis *et al*. (2018)

2. Work types (activities) cover the operations and specialties. These types are coded using architectural textures.
3. The state of intermediate stocks can include their fixed or mobile state, exclusivity and scaffolding. This graphical protocol uses trapezoidal borders.
4. The state of circulation can be inclusive, exclusive, reverse or vertical. The graphical protocol uses various arrow styles.
5. Specialties (resources) are represented by a range of dark-colored fills with normal hues, saturation and brightness; they are subdivided into warm and cold categories.
6. Work locations are represented by a range of light-colored fills with low saturation and high brightness. These light colors allow for the layering of other elements such as textures and text.

3.4. An example using the Chronographic modeling

The abovementioned example from Section 3.1 was scheduled using the Chronographic modeling, which splits the production process into six stages: i) space creation (e.g., the addition of new floors), ii) system installation (e.g., of ventilation ducts), iii) envelopes, iv) space division (e.g., using partitions), v) finishing (e.g., painting), and vi) space closure (e.g., with carpeting).



Code	Process	P1	P2	P3	P4
Spec	Specs, product data & San	x			
Shp	Shop drawing		x	x	x
App	Approval		x	x	x
Fab	Fabrication			x	x
I - C	Instrument. & Control				x

(b)

Fig. 3(a)-3(b) Chronographic model of scheduling for a building floor

These stages are graphically modeled as six layers using various colors and textures. These textures and colors are based on certain modeling approaches, such as the need for a background to ensure easy coordination and graphical schedule optimization (see Figure 3.d). The figure use three of these approaches:

(ii) System installation (in two areas: S1 and S2), modeled in solid grayscale colors (see Figure 3.a1).

iv) Space division (into three areas: P1 to P3), modeled in gray textures (see Figure 3.a2).

v) Finishing (divided into eight zones: Z1 to Z8), modeled in solid colors in a clear range (see Figure 3.a3).

Figure 3.b shows the procurement processes, which can include the following steps: i) transmission of specifications, product data and samples (Spec); ii) transmission of shop drawings (Shp); iii) approval of transmitted documents (App); iv) fabrication of various items in workshops and factories (Fab); and v) instrumentation and control (I–C). These five steps are identified using five colors: pink, yellow, green, blue and orange, respectively. The four processes (from P1 to P4) that were identified in this project used a mix of steps.

Figure 3.c shows the Chronographic model for the example that was modeled using Gantt-Precedence diagram logic in Figure 1. This figure is organized by layer and by zone, it also considers the supply process. As an example, consider the plumbing work: i) the piping and fittings are independently planned according to the three zones (P1 to P3) of the space division; ii)

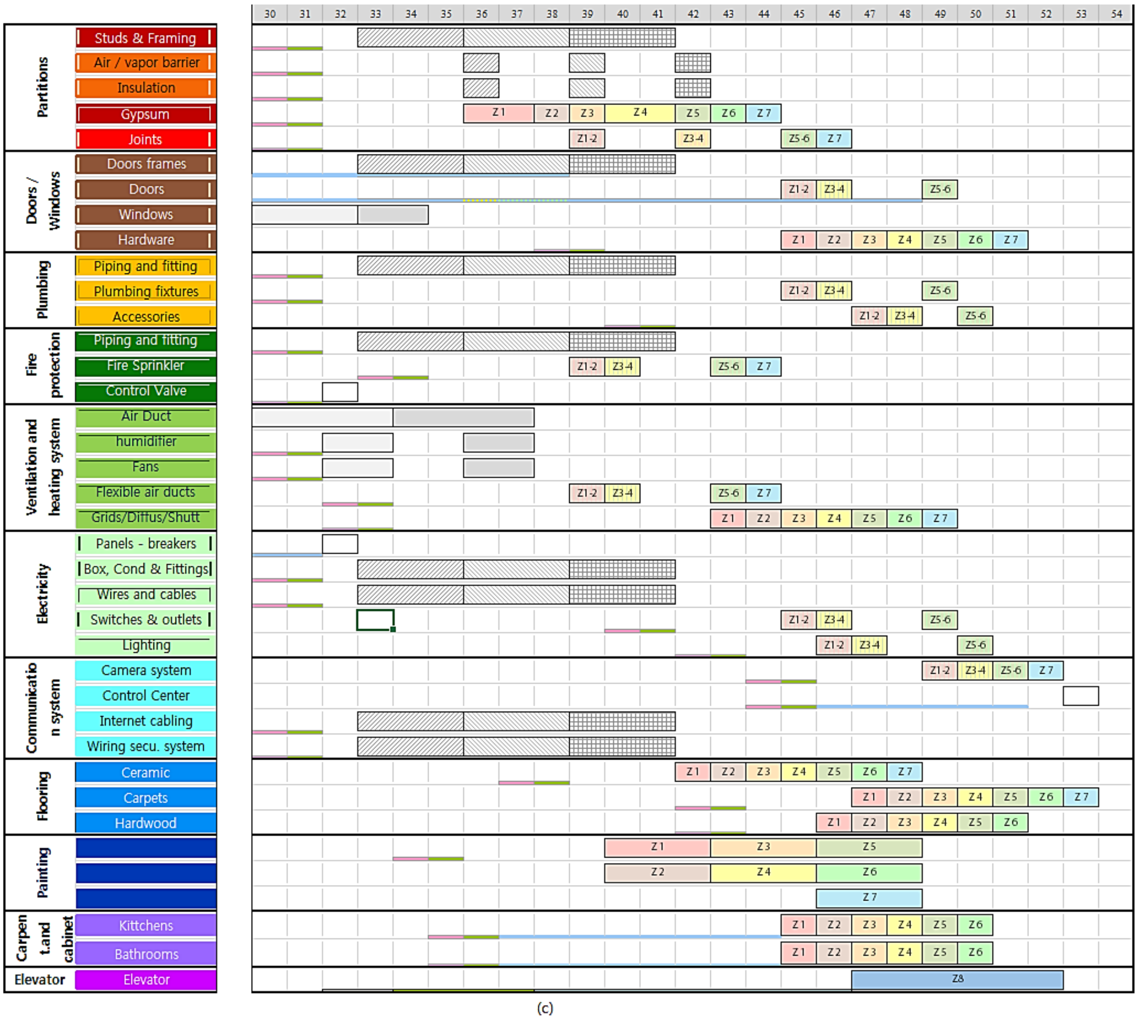


Fig. 3(c) Chronographic model of scheduling for a building floor

the plumbing fixtures are divided according to the eight finishing zones (Z1 to Z8); and iii) the procurement steps are modeled for two activities: the transmission of specifications, product data and samples (Spec) and the approval of the transmitted documents (App).

The same data are presented in Figure 3.d according to the working areas of the various layers and zones. This shows the conflicts in the use of the spaces as well as each space's efficiency. In this figure, the zones are sometimes congested; several conflicts of use are present. As an example, five activities (doors, cabinet, plumbing fixtures, hardware, and switches and outlets) compete in Z1 during Week 45. Based on this model, the manager could thus judge the feasibility of a plan and make the necessary decisions (e.g., delaying or accelerating certain activities). This congestion can cause conflicts between work teams and increase the project's duration and cost. In addition, it can affect the site's climate and demonstrate that the site's management is not ideal. The model also shows that some areas are underutilized during certain periods. For example, there are no activities in zone Z1 during Weeks 43 and 44. This underuse of certain zones unnecessarily prolongs the project.

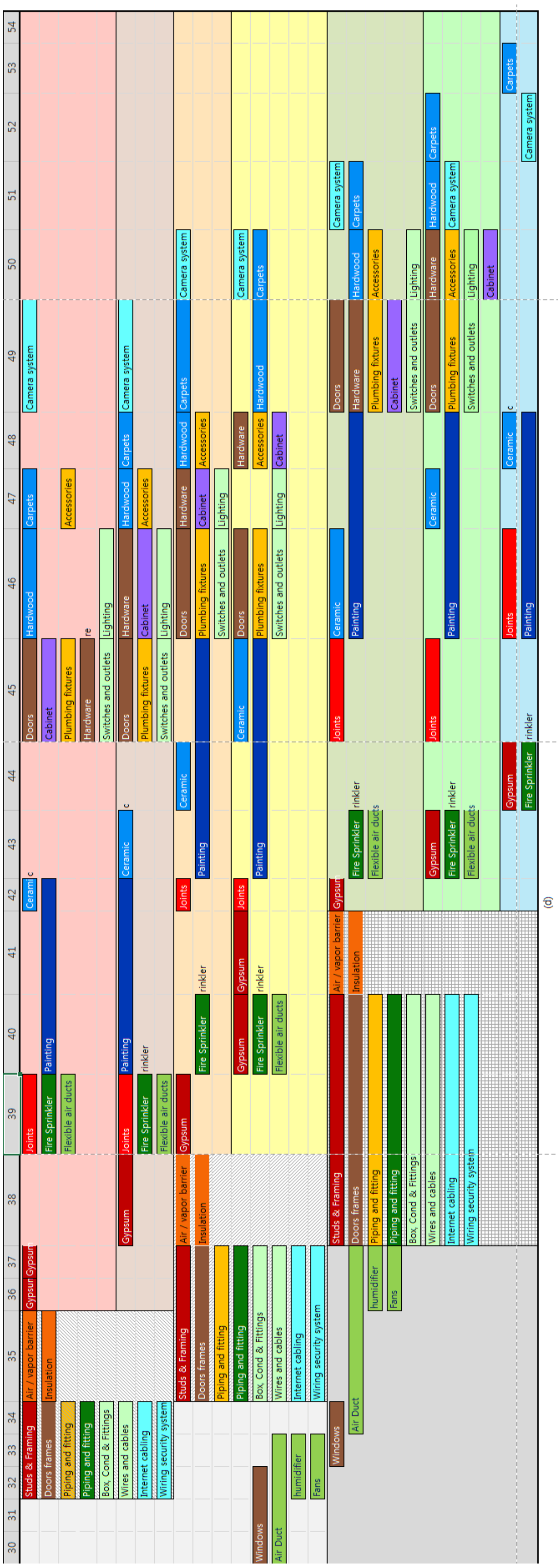


Fig. 3(d) Chronographic model of scheduling for a building floor

Partitions	T									
Studs & Framing	p1	p2	p3					S	A	
Air / vapor barrier	p1	p2	p3					S	A	
Insulation	p1	p2	p3					S	A	
Gypsum	p1	p2	p3					S	A	
Joints	p1	p2	p3					S	A	
Doors / Windows	T									
Doors frames	p1	p2	p3					S	A	F
Doors	z1	z2	z3	z4	z5	z6	z7	S	A	F
Windows	S1	S2						S	A	F
Hardware	z1	z2	z3	z4	z5	z6	z7	S	A	
Plumbing	T									
Piping and fitting	p1	p2	p3					S	A	
Plumbing fixtures	z1	z2	z3	z4	z5	z6	z7	S	A	
Accessories	z1	z2	z3	z4	z5	z6	z7	S	A	
Fire protection	T									
Piping and fitting	p1	p2	p3					S	A	
Fire Sprinkler	z1	z2	z3	z4	z5	z6	z7	S	A	
Control Valve	A							S	A	
Ventilation and heating sy	T									
Air Duct	S1	S2						S	A	F
humidifier	S1	S2						S	A	
Fans	S1	S2						S	A	
Flexible air ducts	z1	z2	z3	z4	z5	z6	z7	S	A	
Grids/Diffus/Shutt	z1	z2	z3	z4	z5	z6	z7			

Electricity	T									
Panels - breakers	A							S	A	F
Box, Cond & Fittings	p1	p2	p3					S	A	
Wires and cables	p1	p2	p3					S	A	
Switches & outlets	z1	z2	z3	z4	z5	z6	z7	S	A	
Lighting	z1	z2	z3	z4	z5	z6	z7	S	A	
Communication system	T									
Camera system	z1	z2	z3	z4	z5	z6	z7	S	A	
Control Center	A							S	A	F
Internet cabling	p1	p2	p3					S	A	
Wiring security system	p1	p2	p3					S	A	
Flooring	T									
Ceramic	z1	z2	z3	z4	z5	z6	z7	S	A	
Carpets	z1	z2	z3	z4	z5	z6	z7	S	A	
Hardwood	z1	z2	z3	z4	z5	z6	z7	S	A	
Painting	T									
Painting	z1	z2	z3	z4	z5	z6	z7	S	A	
Carpentry and cabinet	T									
Kittchens	z1	z2	z3	z4	z5	z6	z7	S	A	F
Bathrooms	z1	z2	z3	z4	z5	z6	z7	S	A	F
Elevator	T									
Elevator	Z8							S	A	F

Fig. 4 Breakdown of project activities based on space and the procurement process

Resolving these conflicts using this inverted planning process (i.e., scheduling the activities and then trying to manage the resources and the use of space) is not easy. The optimal solution is to start planning for resources to be placed in separate zones, as demonstrated using the Chronographic modeling and the Takt-time in the following sections.

Therefore, it is reasonable to conclude that a project plan that is based only on Gantt-Precedence diagrams and current software is insufficient for the effective and efficient management of a building-construction project. However, the presented deficiencies are easily solved with the use of the Chronographic modeling and the Takt-time.

3.5. Gantt-Precedence diagram, zones and the procurement process

When a user tries to plan a project that includes layers and a procurement process using a Gantt-Precedence diagram, the number of activities is immense. The graphical rendering of the resulting schedule also leaves much to be desired, as Fisk (2013) noted.

Figure 4 shows that adding space management to a project increases the number of activities from 47 to 171. This further increases to 250 activities if the procurement process is also modeled. Figure 5 shows a Gantt-Precedence diagram that demonstrates the planning for space and procurement in the erection of wall partitions. This figure indicates that the implementation of a complete project at this level of detail will be complex. In addition, as already discussed, a lower level of detail is insufficient for the effective and efficient management of building construction projects.

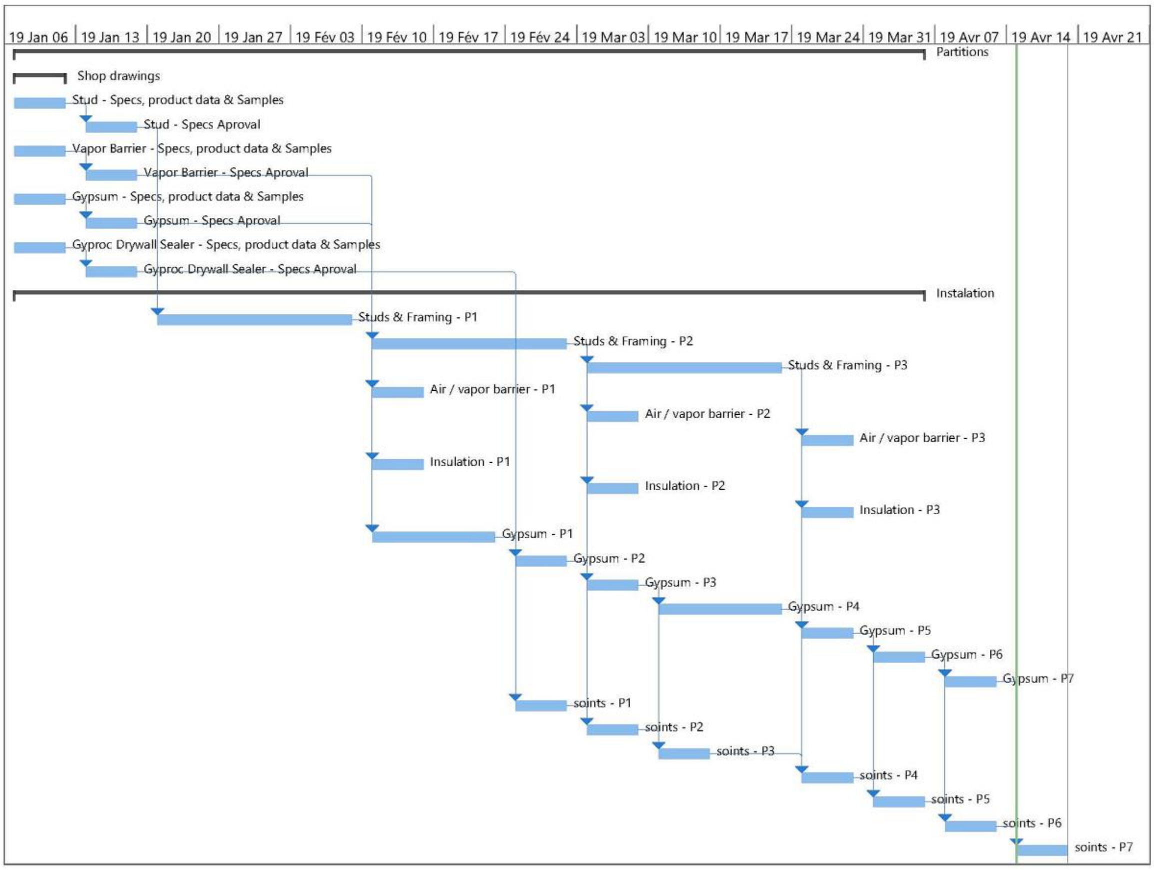


Fig. 5 Gantt-Precedence diagram for wall-partition planning

4. Procurement process and the Chronographic modeling

In the Chronographic modeling method, intermediate stocks occupy spaces, prevent operations and affect the calculation of critical spaces. These stocks artificially increase construction sites' occupancy rates and hinder traffic. When studying circulation on building sites, it is necessary to consider the fact that stocks evolve, as well as the mobility of a given stock. A mobile stock moves easily with workers, but a fixed stock takes up space for a long period. Another point to consider is the nature of the occupation. Stocks can be inclusive (meaning that they do not restrict operations from being done in the same area) or exclusive (meaning that they occupy the whole space). One strategy involves using the pull flows for the majority of supplies and minimizing intermediate stocks. In this strategy, pushed flows are only used for equipment in long supply processes (e.g., boilers, pumps and ventilation equipment). This delivery method is mostly used if delivery in the middle of the project could cause delays. Although manufacturing workshops use pushed flows, their on-site delivery can be controlled. This process likely negatively affects cash flow but does not contribute to congestion. It is a compromise between the cost due to late equipment delivery and the financing cost due to early production (or purchase). JIT must be used for quick-setting materials.

On this basis, the proposed procurement system should be able to manage a wide variety of materials and products while ensuring the required quality, thus reducing stock, time, space and investment requirements, as well as avoiding the need for multiple storage stations. Excessive storage includes that of raw materials, works in progress and finished products that are awaiting successor activities. When such stocks exceed immediate production needs, the result is waste in terms of i) a need for more storage space, which reduces available work space; (ii) an increase in the frequency and severity of traffic jams; iii) a greater need for sorting, storage and cleaning; and iv) additional financing for excessive storage.

The proposed system ensures continuous flow in both production and supply based on workload leveling, takt and spatiotemporal techniques, and visual management (through the empowerment of the workers). In terms of visual management, each worker (or subcontractor) is responsible for planning his or her own orders for materials as the work progresses. This is in contrast to the old habit of hiding problems and acting as if they do not exist; every worker in this system has the power (and even responsibility) to stop production if the operations prior to that worker's intervention do not conform to standards. Visual management is therefore necessary to ensure proper supply and control processes.

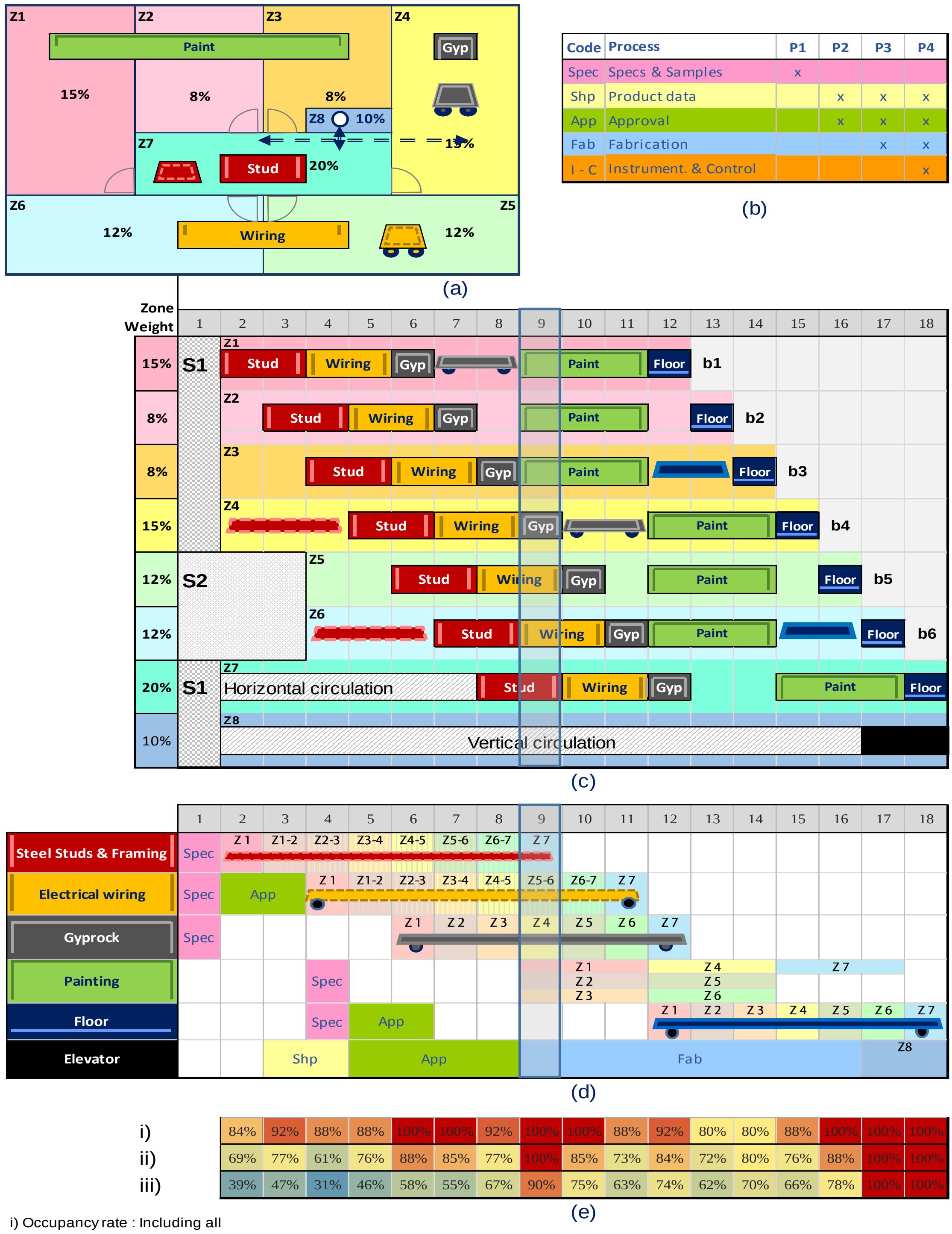
The proposed procurement system considers a tradeoff between economic risks and the risk of material shortage. If the materials and equipment are supplied early in the process, this can reduce capital and lead to a lack of liquidity. Any interest paid as a result increases the cost of the project. Furthermore, this causes a need for additional storage and warehousing, which generates additional costs. It can also aggravate traffic. In addition, the materials can deteriorate or be stolen during storage unless special care is taken. For example, electrical equipment often must be stored in watertight places. Worse still, the expenses that are incurred on surplus stocks do not accomplish anything. The cost of an anticipated supply includes the costs of possession, storage and deterioration. Conversely, however, a delay in supply generates additional costs if the required equipment or materials are not available on time. In some cases, more expensive supply or shipping methods can be used to save time. The availability of materials can also greatly influence timing, particularly for fast-tracked and remote project sites. Shipments always must be carefully planned.

Any strategy should consider liquidity, the borrowing costs for the early procurement and supply of materials, and the cost of delays due to temporary unavailability of materials. A procurement strategy also must consider long supply processes, which generally require document submissions (e.g., shop drawings, technical data, production specifications and samples) for approval by architects and engineers and which thus may require quite lengthy manufacturing processes.

To this end, the proposed procurement method combines the three systems mentioned above: pushed flows for long supply processes (e.g., when custom equipment is needed, as for ventilation, heating, air conditioning, boilers or pumps), the pull system for materials that are available on order (e.g., gyprock and ceramics, and JIT for fast-setting materials (e.g., concrete and bitumen). A model that helps in the planning of continuous workflows will help to eliminate waste by reducing waiting time, using the shortest possible travel distances and minimizing storage to allow for production peaks.

5. Examples of chronographic modeling

With the Chronographic modeling, a project schedule can be presented using both tabular and



i) Occupancy rate : Including all

ii) Occupancy rate : Not including exclusive intermediate stocks

iii) Occupancy rate : Not including exclusive intermediate stocks & circulation

Fig. 6 Chronographic modeling and site management graphical means. As a result, a project schedule can be viewed using several compatible approaches. The planner thus has the ability to switch approaches by changing graphical parameters. A graphic representation that is so easily transformable helps planners to solve problems of various natures; it also simplifies site management and ensures that the visual space can be used as efficiently as possible.

To demonstrate the benefits of the proposed model and to validate the related concepts, two examples are discussed in this section. This validation process is designed to test the model's graphical ability to simulate the construction and procurement processes.

The first example is the scheduling of the partition wall and the finishing for a building floor. The process starts by modeling the teams' execution of activities, as well as their resources in the various zones of each layer using the Chronographic modeling and the Takt-time logic (see Figure 6.c). The same information is subsequently demonstrated using several modeling approaches so as to verify the constraints. Figure 6 shows the procurement process and the occupancy rate for three compatible approaches to presenting the same schedule:

- Figure 2.a shows the site occupation plan and circulation for a certain date (Period 9). This includes the site's resources, activities, intermediate stocks and traffic.
- Figure 2.b defines the various procurement processes, including the construction submissions (workshop drawings, samples, technical sheets and production plans).
- Figure 2.c demonstrates a spatiotemporal approach that shows the construction operations in the foreground and the site spaces in the background. This strategy facilitates optimization and leveling of the site and its resources; the figure also shows the emplacement of activities (ceiling, walls, floor or a combination) and the states of the intermediate stocks, including whether they are fixed or mobile and inclusive or exclusive.
- Figure 2.d considers the activities (or teams) from a second dimension. The operation progress is shown in each zone. This model is also effective for resource allocation and leveling.

The planner can also define the limits of occupation for each location in order to avoid traffic jams (Figure 2.e). The occupancy rate in Figure 2.e.1 includes operations, intermediate stocks and circulation. Figure 2.e.2 excludes intermediate stocks, and Figure 2.e.3 excludes intermediate stocks and circulation.

The second example demonstrates the schedule for a five-story building. Each story is divided into four zones (Z1 through Z4). In addition, the project plans include work on the foundation and roof. The project is divided into 22 work packages (Lot 2-A, which covers excavation, through Lot 16-A, which covers electricity and finishing). Five steps (Spec through I-C) and four processes (P1 through P4) are also identified for the procurement processes.

Color ranges are established to define the five stories, the four areas, the 22 lots and the five procurement steps; for more information, see the legend in Figure 7.

The process starts with the modeling of the execution teams for each floor and zones using the Chronographic modeling and the Takt-time logic (see Figure 7.b). The same information is subsequently presented using several modeling approaches so as to verify the constraints:

- Figure 7.a shows the schedule grouped according to the 22 work packages. This schedule shows the procurement steps and activities by floor and by zone. Using this figure, each team should know its work schedule for each floor and zone. For example, the work package 8-B (door frames) has five sub-activities—one per floor. The procurement process for this package contains three steps (Shp, App and Fab).

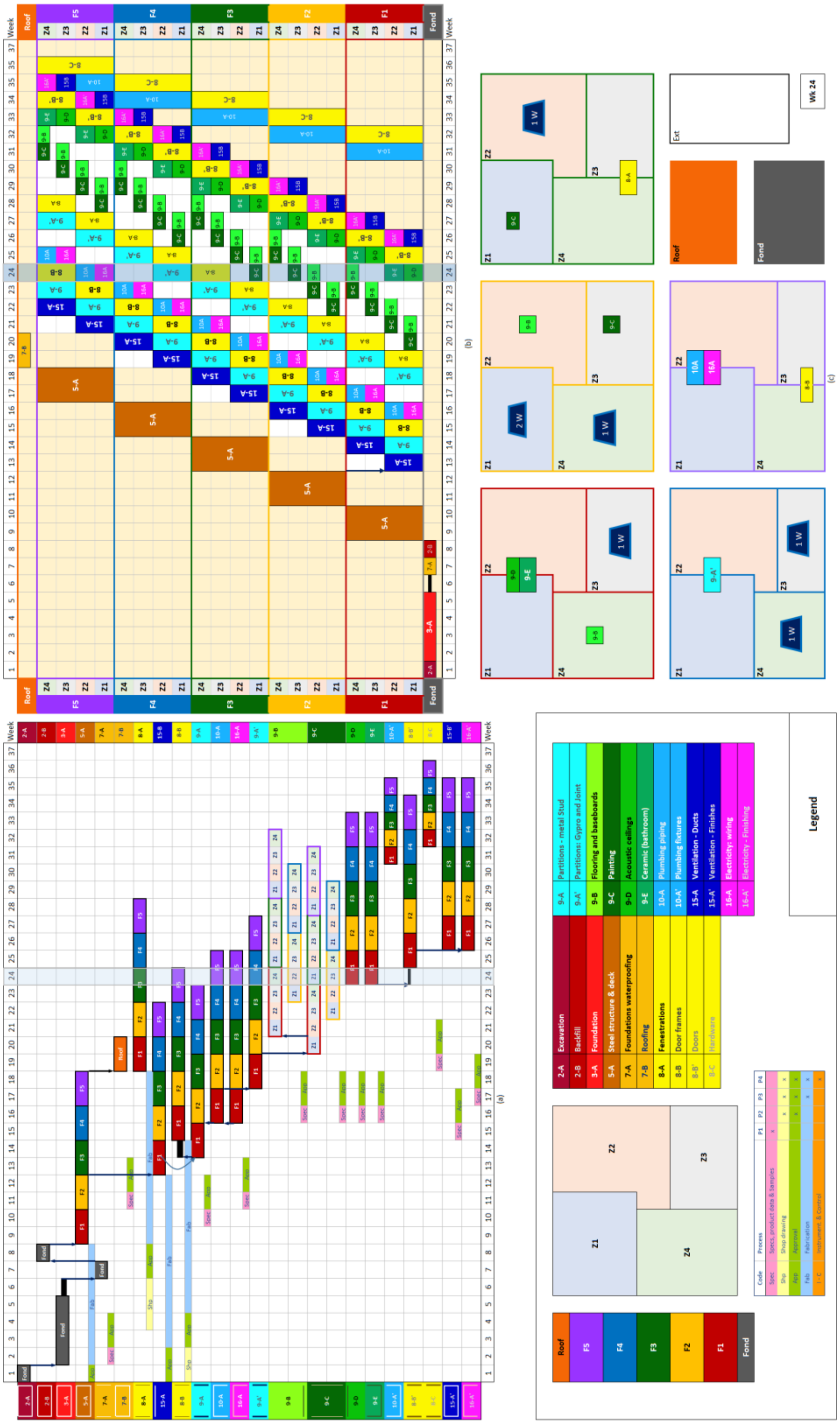


Fig. 7 Schedule for a five-story building using the Chronographic modeling

Technical specific. - Section	TYPE	Description	Supplier	DATE			Approuval
				Submission	2nd Submission	3rd Submission	
				DATE			
				resubmit	RESOUMETTRE	RESOUMETTRE	Date
15820	Sh	Access doors					
15822	Sh	Motorized Registers	Enertrak	14-Jun-2004	5-Aug-2004		16-Aug-2004
15822	Sh	Motorized Registers	aireau	19-May-2004			8-Jun-2004
15823	Sh	Fire registers	aireau	19-May-2004			8-Jun-2004

TYPE **QC:** Quality control **Sh:** Shop drawing **Sa:** Sample **Tc:** Technical sheet **Md:** Model **PP:** Production plan

15721 | 15751 | 15767 | 15781-813 | **15820-23** | 15824 | 15825 | 15831 | 15832à51 | 15852 | 15861 | RC15900 | RC15751

Fig. 8 Details of the shop drawings for the transmission and approval process

The details of the procurement process are shown in independent tables. Figure 8 shows the details of the process for transmitting the specifications, product data and samples; completing the shop drawings; and receiving approval.

- Figure 7.b shows the schedule as grouped by working area (floor and zone). With this approach, it is easy to apply work equally for each team, floor and zone. In this figure, the light yellow color indicates either that a zone it not available yet or that it is blocked from both work and circulation. The white color indicates that the zone is idle and that it can be used for intermediate stock without delaying the project.
- Figure 7.c shows the site plan by building section (foundation, Floors 1 through 5, roof and exterior work). This plan shows the executed work and the available space for intermediate stock in a certain period (Week 24 in this example).
- These two examples fulfill the research objective of defining how planners can model a building construction project using the Chronographic modeling, the Takt-time and the Last Planner System. These examples also demonstrate how the proposed spatiotemporal approach allows planners to schedule two projects while ensuring efficient use of the site, team rotation and the management of intermediate stocks.

7. Conclusıon

In conclusion, neglecting to consider space management during the execution and procurement processes in the construction of building projects negatively affects the outcome of those projects. Current scheduling methods do not account for spatiotemporal constraints, which leads to less than optimal scheduling. This failure causes problems related to overuse and underuse of the available space, which thus affects the project's duration and cost. As a result, the project's schedule and cost estimates turn out to be optimistic, and avoidable site conflicts occur. Intermediate stocks occupy space, prevent operations and affect the calculation of critical spaces. They also artificially increase the occupancy rate and hinder traffic. To study circulation on building sites, it is necessary to consider the fact that stocks evolve. By considering the impact of resources, materials, temporary facilities and the management of working areas using a schedule, the Chronographic modeling simulates a project's real conditions.

This scheduling study considers the balance of work across teams, floors and zones in the execution and procurement processes using the Chronographic modeling and the Takt-time logic. Chronographic modeling is an alternative to traditional methods of scheduling and planning for spaces. The modeling layout's user interface is in the spatial dimension and is based on suitable visual parameters and their associated values. The result is that a project schedule can be presented using various compatible approaches. This organizational approach permits changes in visual approach through the manipulation of graphics via a set of defined graphical parameters.

References

Ala-Risku, T. and Karkkainen, M. (2006), "Material delivery problems in construction projects: A possible solution", *J. Production Economics*, **104**(1), 19-29.

Bell, L.C. and Stukhart, G. (1987), "Costs and benefits of materials management systems", *J. Construct. Eng. Manag.*, **113**(2), 222-234.

Bertelsen, S. and Nielsen, J. (1997), "Just-in-time logistics in the supply of building materials", *Proceedings of the 1st International Conference on Construction Industry Development*, Singapore, December.

Bertin, J. (2005), *Sémiologie graphique*, *les diagrammes - les réseaux - les cartes* (4th Ed.), EHESS, Paris.

Chavada, R.D., Kassem, M., Dawood, N.N. and Naji, K.K. (2012), "A framework for construction workspace management: A serious game engine approach", *Proceedings of the 2012 ASCE International Conference on Computing in Civil Engineering*, June.

Fisk, R.E. and Reynolds, W.D. (2013), *Construction Projects Administration (10th Ed.)*, Pearson Education, London, United Kingdom.

Francis, A. (2013), "The chronographical approach for construction project modelling", *Proceedings of the Institution of Civil Engineers-Management*, *Procurement and Law*, **166**(4), 188-204.

Francis, A. (2016), "A Chronographic protocol for modelling construction projects", *Proceedings of the Institution of Civil Engineers-Management*, *Procurement and Law*, **169**(4), 168-177.

Francis, A. (2017), "Simulating uncertainties in construction projects with chronographical scheduling logic", *J. Construct. Eng. Manag.*, **143**(1), 1-14.

Francis, A. and Miresco, E.T. (2000), "Decision support for project management using a chronographic approach", *Proceedings of the 2nd International Conference on Decision Making in Urban and Civil Engineering*, Lyon, France, November.

Francis, A. and Miresco, E.T. (2002), "Decision support for project management using a chronographic approach", *J. Decision Syst.*, **11**(3-4), 383-404.

Francis, A. and Miresco, E.T. (2006), "A chronographic method for construction project planning", *Canadian J. Civil Eng.*, **33**(12), 1547-1557

Francis, A., Bibai, J. and Miresco, E.T. (2013), "Simulation of scheduling logic using dynamic functions", *Proceedings of the Institution of Civil Engineers-Management*, *Procurement and Law*, **166**(3), 145-158.

Francis, A., Le Meur, E. and Miresco, E. (2018), "Space planning of material flow for building projects: The Chronographical modelling concept", *Proceedings of the 17th International Conference on Computing in Civil and Building Engineering*, ISCCBE, Tampere, Finland, July.

Frandson, A. and Tommelein, I.D. (2014), "Development of a Takt-time plan: A case study", *Proceedings of the Construction Research Congress*, Atlanta, GA, May.

Horman, M.J. and Thomas, H.R. (2005), "Role of inventory buffers in construction labor performance", *J. Construct. Eng. Manag.*, **131**(7), 834.

Keim, D.A. (2002), "Information visualization and visual data mining", *IEEE Transactions on Visualization and Computer Graphics*, **7**(1), 100-107.

Ng, S.T., Shi, J. and Fang, Y. (2009), "Enhancing the logistics of construction materials through activity-

based simulation approach", *Eng*., *Construct*. *Architect*. *Manag*., **16**(3), 224-237.
Ning, X., Lam, K. and Lam. M.C. (2010), "Dynamic construction site layout planning using max-min ant system", *Automat*. *Construct*., **19**(1), 55-65.
Pheng, L.S. and Chuan. C.J. (2001), "Just-in-time management of precast concrete components", *J*. *Construct*. *Eng*. *Manag*., **127**(6), 494-501.
Riley, D.R. and Sanvido, V.E. (1995), "Patterns of construction-space use in multistory buildings", *J*. *Construct*. *Eng*. *Manag*., **121**(4), 464-473.
Riley, D.R. and Sanvido, V.E. (1997), "Space planning method for multistory building construction", *J*. *Construct*. *Eng*. *Manag*., **123**(2), 171-180.
Rischmoller, L., Fisher, M., Fox, R. and Alarcon, L. (2001), "4D planning and scheduling (4D-PS): Grounding construction IT research in industry practice, construction information technology", *Proceedings of CIB W78 International Conference—IT in Construction in Africa*, Mpumalanga, South Africa, May.
Su, X. and Cai, H. (2014), "Life cycle approach to construction workspace modeling and planning", *J*. *Construct*. *Eng*. *Manag*., **140**(7), 1-12.
Su, X. L., Zhang, A.R. and Cai, H. (2012), "GIS-based buffering for construction workspace management, *Construction Research Congress*, West Lafayette, Indiana, 1252-1261.
Thomas, H.R., Riley, D. and Messner, J.I. (2005), "Fundamental principles of site material management", *J*. *Construct*. *Eng*. *Manag*., **131**(7), 808.
Tufte, E.R. (1983), *The Visual Display of Quantitative Information*, Graphics Press, Cheshire, CT, U.S.A.
Winch, G.M. and North, S. (2006), "Critical space analysis", *J. Construct*. *Eng*. *Manag*., **132**(5), 473-481.
Zouein, P.P. and Tommelein, I.D. (2001), "Improvement algorithm for limited space scheduling". *J*. *Construct*. *Eng*. *Manag*., **127**(2), 116-124.

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