

SYSTEMATISING THE CREATION OF LINE OF BALANCE: AN AUTOMATED TOOL FOR MULTI-STOREY BUILDING

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ABSTRACT

Planning in multi-storey buildings is often constrained by manual processes and tacit knowledge, which hinders the systematic application of Lean principles. This paper presents the formalisation of a structured method based on three deterministic spatio-temporal rules—stable rhythm, vertical continuity, and non-crossing—and its instantiation in a computational artefact developed in Excel/VBA under the Design Science Research approach. The automation reduced the processing effort of an otherwise exhaustive manual procedure to a few seconds, allowing the agile exploration of multiple rhythm scenarios. Its application to a real residential project provided a real-data environment for the artefact instantiation, supporting the identification of a schedule recovery potential of 21%, assessed significantly faster and more consistently than through conventional planning approaches. The results demonstrate that the integration between the method and its technological instantiation enhances data-driven decision-making, strengthens operational predictability, and supports the transition towards a more flow-oriented planning system.

KEYWORDS

Lean construction, location-based management, Line of Balance, scenario simulation, BIM.

INTRODUCTION

While the international construction industry faces a long-standing stagnation in productivity (Teicholz, 2013; McKinsey Global Institute, 2017), Lean Construction principles suggests that improvement depends fundamentally on flow stability and the reliability of plan execution (Howell & Ballard, 1999; Koskela, 2000). In repetitive environments, such as multi-storey buildings, this stability is sensitive to rhythm variations, where local delays generate cascading effects that compromise predictability (Laufer & Tucker, 1987). To address this, Location-Based Scheduling (LBS) and the Line of Balance (LoB) have emerged not merely as graphical representations, but as flow-oriented planning and control systems capable of making sequencing conflicts and cadence incompatibilities explicit (Kenley & Seppänen, 2010; Biotto, 2019).

Despite this conceptual maturity, the practical application of the LoB remains constrained by a significant operational bottleneck. Traditional task-based scheduling often fails to capture the spatial dynamics of production, leading to inconsistent overlaps and "gaps" in work progression. Furthermore, studies indicate that manual LoB development is labour-intensive and highly dependent on rework, especially when minor site variations require the complete

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reconstruction of charts (Schramm, 2004; Rodrigues, 2006). This difficulty inhibits scenario experimentation and constrains essential analyses—such as rhythm adjustments and buffer definition—that are vital for mitigating variability (Valente et al., 2013; Lucko et al., 2014). Furthermore, the absence of systematic mechanisms for calculation and forecasting compromises the capacity to respond to deviations, highlighting a persistent need for stronger computational support for location-based methods (Seppänen, 2025).

In the Brazilian context, this gap is exacerbated by uneven digital maturity, where planning practices still rely predominantly on manual routines and spreadsheets (Bezerra & Scheer, 2020; BFB, 2022; Gonçalves & Corrêa, 2024). Consequently, the main barrier to broader adoption of the LoB does not lie in its theory, but in the difficulty of operationally systematising the planning reasoning that underpins its construction. Overcoming this allows for the transformation of tacit knowledge into stable rules, strengthening the use of the LoB as a continuous decision-support instrument.

Accordingly, this paper proposes to operationally systematise the Lean logic underlying the Line of Balance through a computational artefact developed under the Design Science Research (DSR) approach (March & Smith, 1995). By formalising spatio-temporal rules—stable rhythm, vertical continuity, and non-crossing—into computable procedures, the research aims to transform tacit knowledge into a stable decision-support instrument. This study focuses on the development and validation of this artefact in a real multi-storey project, demonstrating how automation enhances data-driven decision-making and identifies a schedule recovery potential of 21% through agile scenario simulation.

RESEARCH METHOD

The research adopted the Design Science Research (DSR) approach, which is suitable for investigations oriented towards the development of artefacts designed to address practice-driven problems and grounded in theory (March & Smith, 1995; Van Aken, 2004). In this study, DSR provides the methodological framework required to address the gap identified in the literature: the absence of a systematised process capable of translating the spatio-temporal logic of the Line of Balance (LoB) into operational and computable rules.

The research process began with a structured diagnosis grounded in the literature and in evidence collected from the analysed project. This diagnosis confirmed that manual LoB development imposes significant limitations on planning, such as rework, inconsistencies, and difficulties in comparing alternative scenarios, particularly in contexts that require frequent updates.

To investigate these limitations in a real-world setting, the case study was selected based on three criteria: (i) the presence of significant schedule delays requiring replanning; (ii) the use of a task-based scheduling approach (MS Project) in a repetitive multi-storey context; and (iii) the availability of detailed planning data, including a BIM model in IFC format. Thus, the selected project is characterised by repetitive typical floors, making it suitable for location-based planning approaches. Also, the BIM model enabled the integration between planning data and building components, supporting modelling and validation processes.

The primary objective of the case study was to apply, test, and refine the proposed conceptual model for Production Planning and Control (PPC), focusing on the systematisation of the Line of Balance and the simulation of planning scenarios supported by BIM-enabled planning. The dataset included the original project programme, activity lead times, number of floors, and qualitative observations collected during site follow-up. Additional input parameters, such as working calendars, productivity rates, and crew configurations, were derived from the broader research framework developed in Gonçalves (2025) and incorporated into the simulation.

Based on the defined dataset and scope, the analytical procedure consisted of three steps: (i) reconstruction of the original Line of Balance from the baseline programme; (ii) generation of a new LoB using the proposed artefact under identical input conditions; and (iii) comparison between both scenarios in terms of flow continuity, conflict occurrence, and production rhythm. Observations were systematically interpreted by identifying deviations from Lean principles, particularly regarding flow stability and work continuity, and spatial compatibility among different activities.

During the design phase, Location-Based Scheduling (LBS) principles were translated into spatio-temporal rules to guide the automated construction of the LoB. Generative artificial intelligence (large language models – LLMs) supported the elicitation and organisation of these rules by assisting in the decomposition of planning reasoning and in testing alternative formulations. As discussed by Mollick (2024), generative AI was employed as support for intellectual work, while decision-making authority and conceptual validation remained under the responsibility of the researcher. This iterative process required a high level of feedback literacy, ensuring that AI-generated suggestions were critically assessed prior to implementation.

Subsequently, the method was instantiated in a computational artefact implemented in Excel/VBA, capable of automatically applying the formalised rules, generating the LoB, preventing line crossings, and accelerating the construction of alternative scenarios. The developed macro materialises the designed method, constituting—according to the typology proposed by March and Smith (1995)—a technological instantiation, that is, the concretisation of a model and a method into a functional tool intended to support production planning.

The evaluation phase was conducted in a real multi-storey project that did not operate under a structured Lean system. This condition enabled testing the artefact against Lean principles—such as stable rhythm, flow continuity, and compatibility among work fronts—within an environment characterised by lead time variability, operational constraints, and recurrent replanning needs. The objective of this stage was to verify whether the computational logic could structure the LoB coherently and make plan incompatibilities explicit. The evaluation was carried out iteratively, with adjustments incorporated based on artefact use, in accordance with the “field utility” criterion proposed by Kasanen, Lukka and Siitonen (1993).

RESULTS

This section presents the research results in three complementary stages: the formalisation of the systematised method for LoB generation, its computational implementation, and the practical application of the artefact in a real residential project. Taken together, these stages demonstrate the operationalisation of the proposed rules, their materialisation in the artefact, and their usefulness in supporting the planning of repetitive production systems.

METHOD SYSTEMATISATION AND INSTANTIATION

The main outcome of this research is the formalisation of a systematised method for generating the Line of Balance and its corresponding instantiation in a computational artefact developed in Excel/VBA. The method organises the spatio-temporal logic of repetitive production into a set of rules that eliminate the imprecision and subjectivity typical of manual LoB development, enabling planners to focus on the strategic analysis of scenarios.

To operationalise this logic, the method adopts a standard execution flow structure as an input premise, which establishes the typical operational sequence of residential projects (Gonçalves, 2025). Although the detailed definition of this production flow structure is not within the scope of this study, it provides the necessary sequencing for the artefact to systematically apply the three fundamental rules governing production behaviour:

- **Rule 1: Stable Rhythm and Spatial Variability** – the slope of each LoB line is defined by the lead time, ensuring that the plan reflects the rhythm specified by the planner. The distinguishing feature of this rule is its integration with productivity indices: the artefact calculates the required workforce density and makes explicit when resource concentration exceeds predefined occupancy thresholds. While the detailed calculation of workforce sizing and occupancy rates falls outside the scope of this paper, these parameters are incorporated as input conditions to ensure the operational feasibility of the generated scenarios;
- **Rule 2: Vertical Continuity and Deterministic Precedence** – this rule enforces that an activity can only advance to the upper floor after completion of the same task on the lower level, respecting the repetitive nature of the system. By applying this logic deterministically, the artefact ensures flow continuity, preventing the schedule from generating physically infeasible overlaps or “gaps” in work progression. Such vertical stability is essential for mitigating the cascading effects of local delays, as discussed by Laufer and Tucker (1987);
- **Rule 3: Non-Crossing Logical Core** – considered the core of the method, this rule prevents work fronts with different rhythms from overlapping in space–time. The initial position of each line is calculated by simultaneously considering lead time, vertical precedence, and predecessor activities. To enable this ordered chaining, the artefact applies an initial adjustment—a gap—that functions as Work-in-Progress (WIP) distributed along the building. The mathematical formalisation of this adjustment is detailed in the Computational Implementation section (Table 1).

The integration of these rules allows the artefact to automatically generate a complete and coherent LoB, responding immediately to changes in lead times, quantities, production batches, or sequencing. By eliminating the need for extensive manual reconstruction, the solution consolidates the LoB as a continuous decision-support instrument, enhancing the planner’s ability to explore schedule recovery scenarios with greater agility and technical reliability.

During application in the empirical study, the artefact underwent incremental adjustments aimed at improving graphical output legibility, initial line behaviour, and adaptability to different floor configurations. These enhancements were achieved through iterative cycles characteristic of Design Science Research (DSR), in which the outputs generated by the tool were continuously compared with observed production logic on site and with Lean Construction principles. Throughout this process, artificial intelligence acted as a cognitive partner supporting critical analysis and the reorganisation of planning rules, assisting in the identification of inconsistencies and the progressive refinement of the solution, without replacing technical judgement or the researcher’s empirical validation.

In summary, the results indicate that the systematisation of spatio-temporal rules and their computational instantiation contribute to improving both the consistency of the Line of Balance and the planner’s analytical capacity. Increased agility in scenario generation and revision enables more informed decision-making and flow management aligned with real production needs, consolidating the integration between the method and the artefact as the primary practical contribution of this research.

From a Lean Construction perspective, the proposed rules do not operate merely as analytical interpretations, but as embedded decision-making mechanisms within the planning process. Stable rhythm operationalises flow consistency through explicit control of production rates; vertical continuity enforces uninterrupted workflow across locations; and non-crossing ensures the elimination of spatio-temporal conflicts among crews. In this sense, Lean principles are translated into computable planning constraints, actively shaping system behaviour rather than retrospectively explaining it.

ARTEFACT IMPLEMENTATION

The mathematical logic of the artefact was developed by formalising planning rules into deterministic expressions, ensuring that Lean premises—such as stable rhythm and flow continuity—were embedded directly into the code. This development resulted from a collaborative effort involving the researcher, who defined the planning logic, and a programming consultant, who co-structured the algorithmic core. Generative AI models, specifically ChatGPT (OpenAI, 2024) and DeepSeek (DeepSeek-AI, 2024), served as auxiliary tools for code validation, rule decomposition, and reinterpreting unstable behaviours identified during development.

To manage algorithmic complexity and facilitate debugging, the implementation in Excel/VBA was modularised into three independent sets of routines, allowing for incremental testing and greater control over intermediate results. The simplified architecture of the proposed artefact and its functional modules are illustrated in Figure 1.

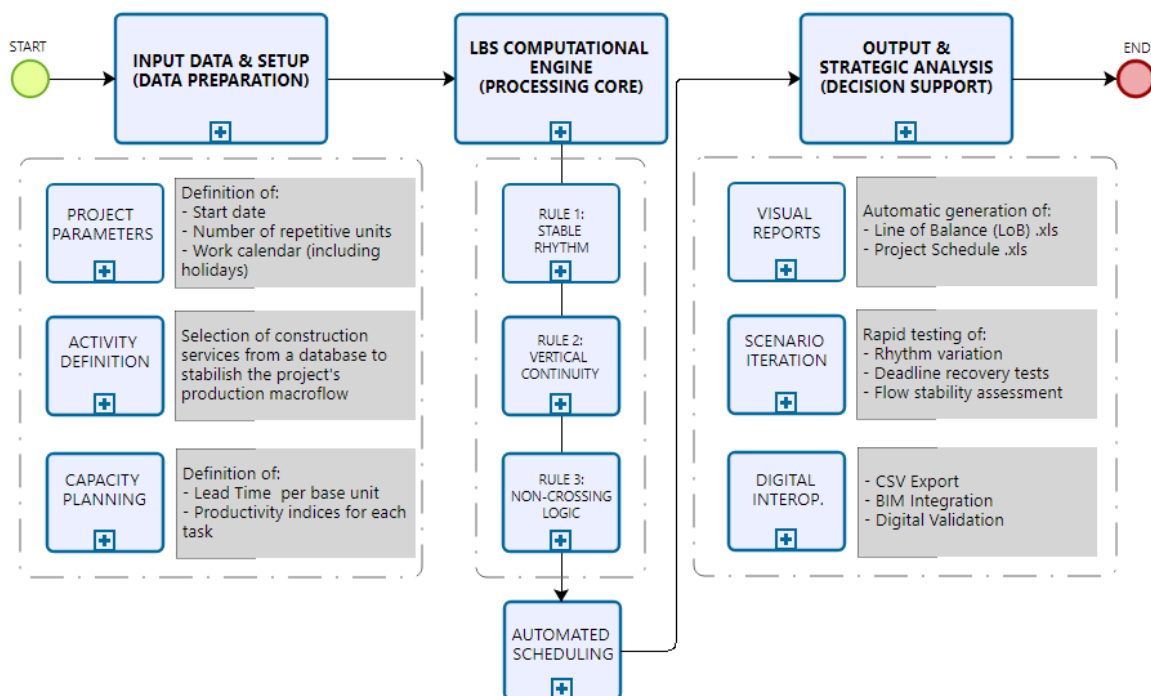


Figure 1: Simplified architecture of the proposed artefact

The artefact's operation is supported by auxiliary forms that handle critical inputs, such as project parameters, customisable holiday calendars, and service selection from a central database. The main module coordinates the planning workflow by iterating through services to calculate start and finish dates while enforcing vertical continuity and preventing work front overlaps. This automated process transforms the traditionally labour-intensive task of constructing a Line of Balance into a systematic procedure.

A central feature of the logic is the initial gap adjustment for activities with differing rhythms, which ensures successor activities maintain progress compatible with predecessors, preventing overtaking between work fronts along the building height and ensuring coherence in schedule construction. This adjustment, functioning as Work-in-Progress (WIP) distributed along the building height, is formalised through an adaptation of takt-based expressions (Table 1). Finally, a CSV export routine was included to empower interoperability with BIM environments, simplifying the linkage between planning data and building models, which

strengthens the reliability of the generated scenarios, and enable the Line of Balance to be validated primarily within a digital environment.

Table 1: Relationship between Takt Time and Gap Calculation at activation

ASPECT	<i>TAKT TIME</i>	<i>GAP CALCULATION</i>
EXPRESSION	$Total\ Duration = (N_{rep} - 1) \times Takt$	$Gap = (LT_p - LTC_s) \times N_{rep} - 1$
VARIABLES	N_{rep} : number of repetitive units (e.g., floors) $Takt$: desired production rhythm	N_{rep} : number of repetitive units (e.g., floors) LT_p : lead time of the predecessor activity LT_s : lead time of the successor activity
OBSERVATION	The subtraction of one unit (1) accounts for the discrete-time representation of the system, in which working days are used as the basic temporal unit for scheduling and gap allocation.	

CASE STUDY

The method was applied to a multi-storey residential project comprising 26 floors, with a total planned duration of approximately 30 months, and the production system included 28 sequential activities organised across repetitive units (floors). For this study, the simulation focused on the typical floors from the 6th to the 19th level (1st to 14th), given their high degree of repetitiveness and representativeness within the overall production system.

The initial Line of Balance (LoB), derived from the MS Project schedule, revealed discontinuities, activity overtaking, and inconsistent production rhythms, along with unsystematised parallelism. These issues compromised flow predictability and hindered the identification of spatial and temporal conflicts between work fronts. In some cases, physically infeasible sequences were observed, such as embedded electrical installation advancing ahead of structural completion (**Error! Reference source not found.a(i)**) and the final checklist activity preceding window frame installation (**Error! Reference source not found.a(ii)**). These deviations indicate weak standardisation and low compatibility among work fronts, increasing the risk of cumulative delays.

Based on the lead times used in the original schedule and the quantities defined for the base unit, the artefact automatically generated the Line of Balance (b), resulting in a continuous and coherent representation aligned with technical constraints and dependencies. The new approach eliminated activity overtaking, re-established critical precedencies and consolidated a stable vertical flow, with work fronts operating at compatible rhythms, while maintaining the same project completion date as the baseline. This demonstrates that flow consistency can be achieved through plan reorganisation without extending the overall project duration.

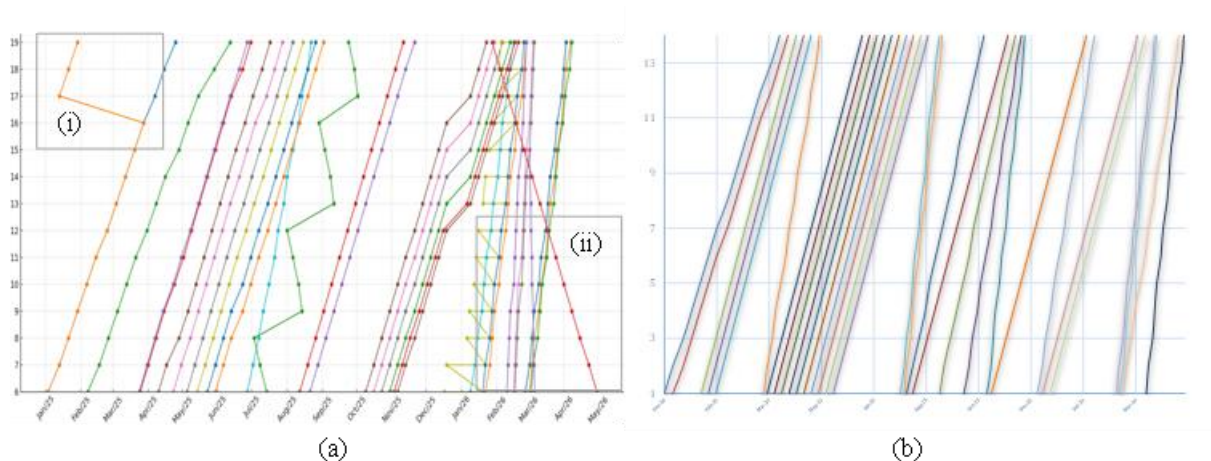


Figure 2: Case study (a) initial Line of Balance (b) balanced Line of Balance

Supporting indicators derived from project data were considered to ensure the operational feasibility of the generated scenarios, including aspects related to production capacity and workload distribution. These parameters were incorporated as inputs to the simulation, supporting the validation of the defined lead times within realistic execution conditions.

At the time of analysis, the project was experiencing a delay of 49 working days, primarily associated with the foundation phase, which required subsequent replanning of the repetitive production stages. By this stage, the structural works were nearing completion, and downstream activities were progressing under relatively stable conditions, creating an opportunity to evaluate alternative planning scenarios.

For the purposes of this study, the simulation scope was defined from the start of the third work package (vertical shafts) on 18 March 2025, up to 30 January 2026. This end date corresponded to a target 49 working days earlier than the original planned completion of the checklist for the 19th floor (08 April 2026), which was adopted as the reference milestone for the analysis.

In this context, to evaluate the artefact's performance, a takt-based replanning strategy was applied to standardise production rhythm across work packages. The simulation considered a planning horizon of 229 working days, covering 28 sequential activities distributed across 14 repetitive units (floors), resulting in a calculated takt time of 5.6 working days, which was rounded down to 5 days due to the discrete nature of planning in working days, a common practice in residential construction.

A comparative summary of the baseline programme, the target defined by the site team, and the artefact-generated scenario is presented in Table 2.

Table 2: Comparison of planning scenarios: baseline x artefact simulated scenario

Metric	Baseline Programme	Target Scenario	Artefact Scenario
Start Date	18 Mar 2025	18 Mar 2025	18 Mar 2025
Completion Date	08 Apr 2026	30 Jan 2026	19 Jan 2026
Total Duration (working days)	277	229	220
Schedule Reduction (working days)	-	49	58
Schedule Reduction (%)	-	18	21
Scenario Type	Original Programme	Site Target	Simulated Scenario
Planning Approach	Task-based (MSP)	Target Deadline	Takt Planning
Buffers Applied	No	-	Yes

As shown in Table 2, the baseline programme presented a total duration of 277 working days. In response to this delay, the site team established a target completion date of 30 January 2026, corresponding to a reduction of 49 working days (18%) relative to the original programme. Using this target as a reference, the artefact was employed to simulate a takt-based replanning scenario. The results indicate that the resulting programme achieved a total duration of 220 working days, corresponding to a reduction of 58 working days (21%) compared to the baseline, exceeding the site target by 9 working days. Besides the numerical reduction, the results demonstrate that schedule compression can be achieved while maintaining flow consistency, supported by a standardised production rhythm and the introduction of buffers at critical points in the sequence. This highlights the artefact's capability to rapidly generate and evaluate takt-based scenarios, balancing flow acceleration with production stability.

Beyond correcting inconsistencies in the original plan, the artefact supported schedule recovery through structured replanning. Given the delays associated with the extended foundation phase, it became necessary to evaluate alternative production rhythms and crew configurations in a rapid and reliable manner. This capability was made possible by the artefact, which permitted near-instantaneous testing of multiple scenarios, making emerging incompatibilities explicit and allowing their impacts on vertical progression to be assessed. In contrast, a manual approach would require successive reconstructions and entail a high risk of error. Thus, this process enabled planners to iterate across different lead time configurations, assess impacts on duration and execution capacity, and evaluate, in a robust manner, the feasibility of sequence adjustments and rebalancing among work fronts.

From this perspective, the case study functioned as a real-data environment for testing the artefact instantiation, enabling a structured comparison between the original planning approach and the artefact-generated solution. The results demonstrate the artefact's ability to systematically eliminate inconsistencies, improve flow continuity, and support more coherent production planning. The contribution of the study therefore lies in the generation of technically consistent and Lean-aligned planning scenarios based on real project data.

Overall, the findings confirm that the method and its computational implementation produce a technically consistent Line of Balance aligned with Lean principles. By making explicit the

relationships between production rhythm and work front interactions, the artefact supports flow stabilisation and reduces decision-related variability, facilitating replanning in delay scenarios. More than a graphical tool, it operates as a flow-oriented planning system, translating the theoretical premises discussed by Biotto (2019) and the need for proactive control emphasised by Seppänen (2025) into a more stable and reliable planning practice.

DISCUSSION

The application of the artefact demonstrates that the formalisation of spatio-temporal rules effectively overcomes the limitations of traditional task-based schedules, which often fail to represent flow and compatibility among work fronts. As highlighted in the literature, the main constraint associated with the Line of Balance (LoB) does not lie in its theoretical foundation, but in its dependence on manual processes and tacit knowledge. By translating this knowledge into deterministic and computable rules, the artefact operationalises Lean principles within the planning process, letting the LoB to function as a flow-oriented Production Planning and Control (PPC) system rather than merely as a descriptive graphical representation.

Importantly, the case study illustrates how the artefact systematically resolves planning inconsistencies that are difficult to identify in conventional schedules. For instance, the original programme allowed embedded electrical installation to advance prior to structural completion, a physically infeasible condition. This inconsistency was eliminated through Rule 2 (Vertical Continuity) and Rule 3 (Non-Crossing), which enforce logical sequencing and prevent spatial-temporal conflicts between crews. More broadly, the artefact restores technical precedencies and empower vertical flow stabilisation, reinforcing production coherence across repetitive units.

From a computational perspective, the ability to generate new LoB versions within seconds directly addresses the need for stronger digital support for location-based planning methods, as emphasised by Seppänen (2025). While identifying alternative scenarios is theoretically possible through manual processes, the effort required to reconstruct and validate multiple LoB configurations often limits their practical use. In this study, automation enabled rapid and reliable iteration across different production rhythms, revealing a potential schedule reduction of 21%, exceeding the 18% initially estimated by the site team. More importantly, this process ensured that accelerated scenarios remained technically consistent, avoiding the introduction of new conflicts or flow disruptions that are common in manually adjusted plans.

More than supporting scenario generation, the artefact contributes to the digitalisation of planning practices by enhancing interoperability with BIM environments. The use of structured outputs (CSV) simplifies the linkage between planning data and building models, reducing manual effort and integration errors. This capability supports the validation of planning logic within a digital environment, strengthening plan reliability and facilitating the adoption of Lean-based approaches in practice.

Despite its advantages, the proposed approach is based on deterministic planning assumptions that may not fully capture the variability inherent to construction processes. The artefact operates on predefined lead times and continuous production logic, which do not explicitly account for disruptions such as temporary constraints.

As a result, while the generated scenarios are technically consistent and aligned with Lean principles, their implementation may require adjustments to accommodate operational contingencies that fall outside the scope of the model. Importantly, the generated planning files remain fully editable, allowing planners to introduce manual adjustments after simulation. In this sense, the artefact should be understood as a structured planning support tool, providing a stable baseline for decision-making rather than a complete representation of site dynamics.

Taken together, the findings reinforce that the contribution of the study lies in embedding Lean principles into deterministic planning rules, enabling their consistent application within a

computational environment. Rather than relying on expert judgement alone, the artefact provides a structured mechanism to support flow-oriented decision-making, expanding the practical applicability of location-based planning methods.

This contribution is synthesised in Figure 3, which presents a conceptual framework linking planning inputs, Lean-based rules, computational implementation, and production outcomes. It also highlights the role of digital tools in bridging the gap between theoretical constructs and practical implementation, supporting both analytical evaluation and decision-making in production planning.

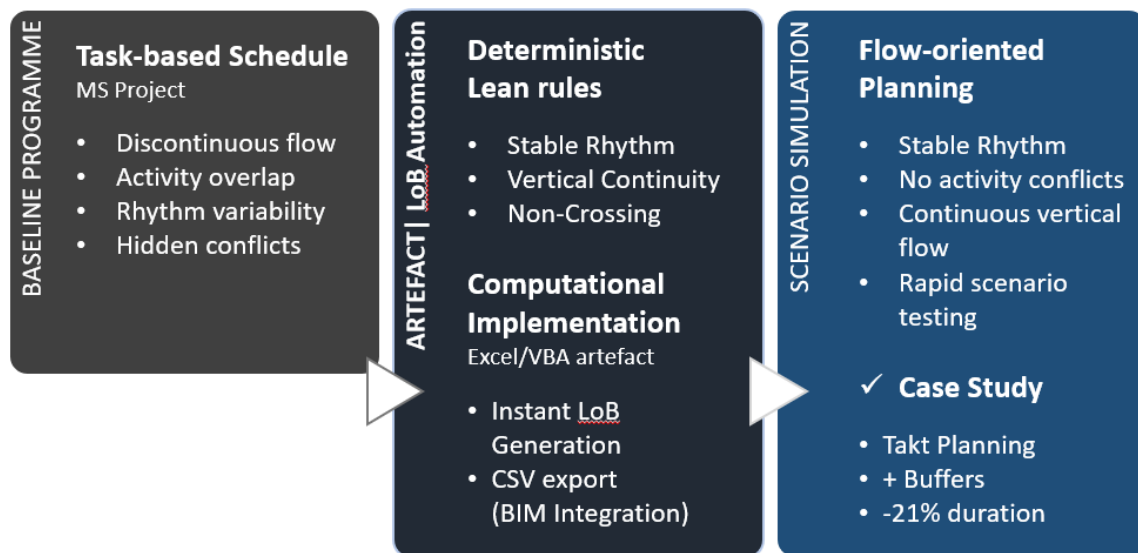


Figure 3: From task-based scheduling to flow-oriented planning through LoB Automation

CONCLUSION

The main theoretical contribution of this research lies in the transformation of tacit planning knowledge into a systematic and computable method. By formalising three fundamental rules—stable rhythm, vertical continuity, and non-crossing—the study addresses an operational gap that has historically limited the effective use of the Line of Balance (LoB). This systematisation ensures that flow stability is not merely an intention, but a direct outcome of deterministic rules instantiated within a technological artefact, thereby embedding Lean principles into the planning logic itself and enhancing schedule technical consistency while supporting flow-oriented Production Planning and Control (PPC).

From a practical perspective, instantiating the method in Excel/VBA demonstrated high field utility by reducing an exhaustive manual processing effort to a matter of seconds. This agility removes the barrier of rework and enables planners to explore multiple rhythm and cadence variations almost instantaneously. Furthermore, structuring outputs in interoperable formats (CSV) simplifies integration with BIM models, supporting the linkage between planning data and building components and lowering practical barriers to digital adoption on site, thus contributing to the digitalisation of Lean planning practices.

It is important to emphasise that the artefact does not replace the planner's role, but rather restructures the decision-making process by providing a consistent analytical foundation for strategic adjustments. Decision-making and conceptual validation remain under the professional's full responsibility, allowing the planner to move from manual task execution towards proactive flow management. In this sense, the artefact expands the planner's capacity to evaluate and compare planning scenarios, reinforcing a shift from reactive adjustments to data-informed and flow-oriented decision-making. In this context, technology acts as a

cognitive partner that provides technical rigour, while the intentionality of Lean planning remains firmly grounded in human judgement.

LIMITATIONS AND FUTURE WORK

Although the results confirm the robustness of the artefact for the base unit of multi-storey buildings, this research is based on a single case study and was limited to internal production sequence planning. In this sense, the applicability of the proposed method is subject to specific boundary conditions and is particularly suitable for projects characterised by repetitive production units, standardised production sequences, and consistent lead times between floors, which enable a stable production rhythm.

Conversely, its effectiveness may be limited in contexts involving high levels of customisation, significant variability between units, or strong interdependencies with external processes, such as façade works, external areas, or complex logistical constraints. In such cases, additional modelling layers or hybrid approaches may be required.

Future work may extend the algorithmic logic to include façade works, external areas, and site logistics, as well as to deepen bidirectional integration with complete BIM models. Continuing this line of investigation will further strengthen the digitalisation of Lean planning, bridging accessible tools with proactive control routines and enhanced operational predictability.

These findings provide analytical insights that may support similar applications in comparable production contexts.

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