Sustainable building production adopting an optimized BIM phasing system

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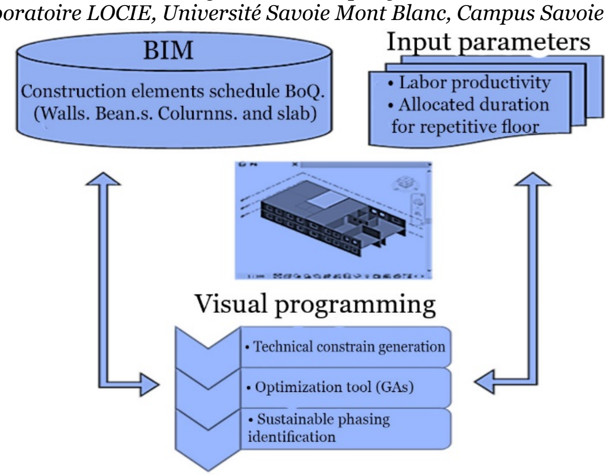

- ✓ *Better balanced quantities of workhours.*
- ✓ *Improving productivity and profitability of used construction resources.*
- ✓ *Reducing around 10% of labor and 25% of non-used formwork.*
- ✓ *Improving site safety conditions.*

ABSTRACT: Sustainable building production could be achieved through better economic efficiency, reduced site waste, and a safe working environment. The identification of the creation phase for each element in the building information model (BIM) is manually done by experienced engineers able to integrate technical construction constraints and an appropriate workflow of construction activities. It is a difficult and complex task to be done. Experienced engineers iterate this operation several times until an adequate solution is achieved without real possibility of optimization. The development of an assistance tool to optimize phase identification of BIM elements included in the repetitive floor plan considering varied evaluation criteria and technical construction constraints should lead to significant economic and environmental profits: reduction of needed construction resources and related waste, improvement of construction quality, and better conditions of site safety. The optimization tool presented in this paper provides better solutions for repetitive floor plans specifically through balanced quantities of work hours and a lower quantity of needed formworks. A reduction of around 10% of labour and 25% of non-used formwork is achieved, which significantly improves site safety, productivity, and profitability. The validity of the presented results is substantiated by multiple examples from real construction sites that have been analyzed in this study.

Keywords: BIM, Optimization. Sustainable building.

إنتاج المباني المستدامة باستخدام نظام الفترات المُحسّن في نمذجة معلومات البناء (BIM)

علي إسطنبولو, عماد ع. عمر, محمد الجمعة

الملخص: يمكن تحقيق إنتاج المباني المستدامة من خلال تحسين الكفاءة الاقتصادية، وتقليل نفايات الموقع، وتوفير بيئة عمل آمنة. يتم تحديد مرحلة الإنشاء لكل عنصر في نموذج معلومات البناء (BIM) يدويًا بواسطة مهندسين ذوي خبرة قادرين على دمج القيود الفنية للبناء وسير عمل مناسب لأنشطة البناء. هذه مهمة صعبة ومعقدة للغاية. يقوم المهندسون ذوو الخبرة بتكرار هذه العملية عدة مرات حتى يتم تحقيق حل مناسب دون إمكانية حقيقية للتحسين. إن تطوير أداة مساعدة لتحسين تحديد المرحلة لعناصر نموذج معلومات البناء (BIM) المتضمنة في الخطة الطابقية المتكررة مع مراعاة معايير التقييم المتنوعة والقيود الفنية للبناء يجب أن يؤدي إلى تحقيق أرباح اقتصادية وبيئية كبيرة: تقليل الموارد اللازمة للبناء والنفايات المرتبطة بها، وتحسين جودة البناء، وتحسين ظروف سلامة الموقع. توفر أداة التحسين المقدمة في هذه الورقة حلولاً أفضل للخطط الطابقية المتكررة من خلال تحقيق توازن في كميات ساعات العمل وكمية أقل من قوالب الصب اللازمة. يتم تحقيق تقليل حوالي 10% من العمالة و25% من قوالب الصب غير المستخدمة، مما يحسن بشكل كبير من سلامة الموقع والإنتاجية والربحية. تستند صحة النتائج المقدمة إلى أمثلة متعددة من مواقع البناء الحقيقية التي تم تحليلها في هذه الدراسة.

الكلمات المفتاحية: نمذجة معلومات البناء (BIM)، التحسين، المباني المستدامة.

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1. INTRODUCTION

The good productivity and profitability of a construction site depend considerably on the definition of the daily work plan repeated from one floor to another in a multistorey building project. This repetitive work could be named the "Repetitive floor construction cycle". The cycle`s duration is identified as the period of completion of the vertical and horizontal construction elements of the repetitive floor. Figure 1 shows an example of a six-phase cycle. The slab of the repetitive floor is divided into a number of zones equal to the cycle`s phase number (six-floor zones). A cycle describes the methodical and successive use of construction resources. In figure 2, construction activities carried out during phase one of the cycle are presented. Those activities include casting walls in completed slab zones, casting slab zone number 4, and installing formworks for slab zone number 5. Figure 3 represents activities carried out during the second phase of the cycle including casting walls in completed slab zones, casting slab zone number 5, and installing formworks for slab zone number 6.

The repetitive floor construction cycle strongly influences the working conditions and productivity of the site. Currently, the identification of construction elements realized in each phase of the floor cycle is developed manually. It is a difficult and complex operation to carry out. In fact, experienced people (engineers, site supervisors, site managers, etc.) able to quickly incorporate the multiple construction constraints do not develop cycle plans easily or without several attempts. Factors like construction equipment efficiency, needed human resources, profitability and financial margin of the site are mainly influenced by cycle plans which are developed without a real possibility of optimization. (Leung, 2003) highlighted the importance of a balanced floor construction cycle to achieve floor cycle time savings. Also, it is cited that manual resource levelling is complex and difficult and the optimum solution cannot be easily found.

(Bernegger, 2022) used BIM and GIS data to explore the possibility of optimizing the construction project's sustainability. It is highlighted that a high level of understanding of the complexity of planning accompanying processes is required.

(Naneva, 2020) indicated that there is a high potential to reduce needed material resources for building construction projects. It is anticipated to use BIM techniques continuously in each building phase over the entire building process.

(Dasović, 2019) aimed to identify the optimal location of the crane on the construction site and minimize the crane operation cycle using an active BIM approach. 34.7 %. of time-saving is achieved. The needed information to identify the crane's optimal location is provided by a dynamic system integrating BIM and optimization techniques.

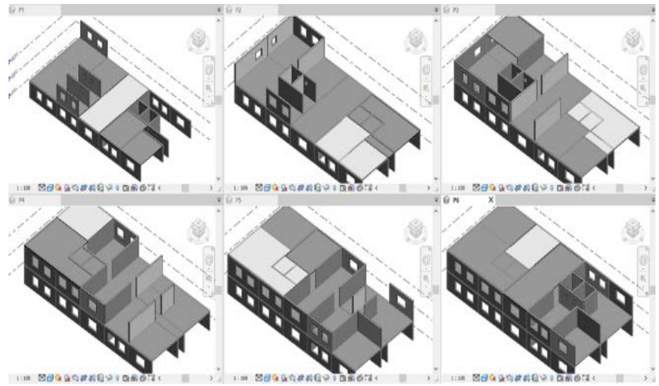

Figure 1: Six phases cycle.

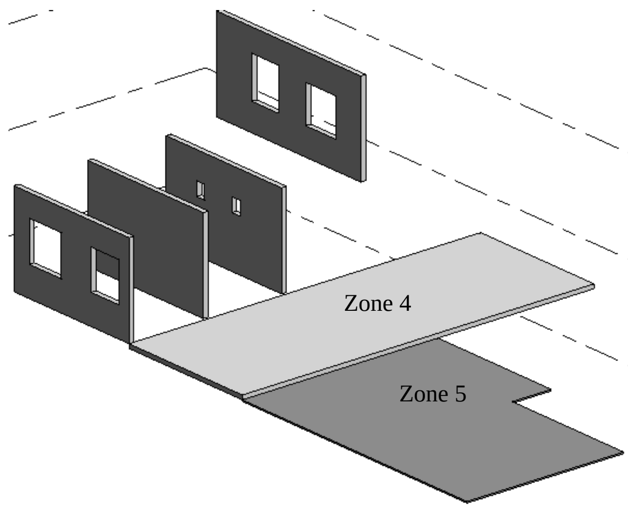

Figure 2: Construction elements created in Phase 01.

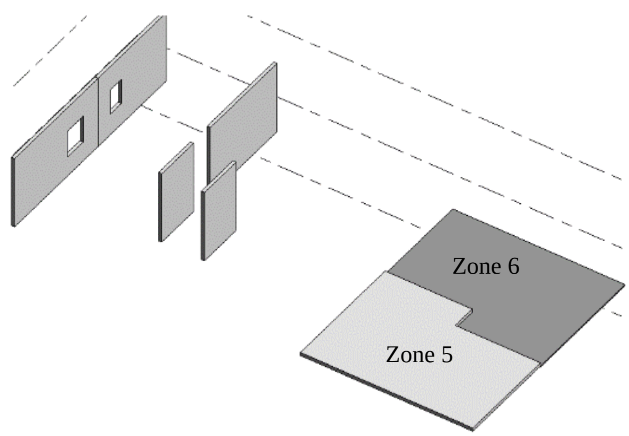

Figure 3: Construction elements created in phase 02.

(Fazeli, 2024) developed an optimization algorithm integrated into visual BIM models to automatically estimate project completion time. It`s highlighted that BIM parametric elements are interrelated and provide more detailed cost, time, and sustainability evaluation capabilities.
(Sompolgrunk, 2023) highlighted a strong need to apply innovative approaches in calculating the time and cost of projects instead of existing approaches of manual estimations. Advanced approaches could lead to productive, efficient, quality, and sustainable construction projects.
(OLAWUMI, 2018) identified the factor "Technical competence of staff" as one the most critical factors to improve the integration of both BIM and sustainable practices in construction projects.
(Križaić, 2023) detected a low level of construction automation. Optimal results in construction could be achieved by using artificial intelligence and digitization.
(Carvalho, 2024) focused on the utility of BIM-based sustainability assessment to improve buildings' sustainability performance in the early stages of the project. It is highlighted that BIM-based procedures have a high potential of gathering valuable insights and providing broader and detailed building circularity assessment which leads to high-performance constructions.
(Lim, 2019) developed a computational BIM-based optimization model for building envelope overall thermal transfer value (OTTV) and construction cost. A BIM tool (Revit), a visual programming tool (Dynamo), and a multi-objective optimization (MOO) algorithm were used. Construction costs are increased by 19.64%. However, a 44.78% reduction of OTTV is achieved.
(Yu, 2023) developed a time-cost optimization process by combining BIM technology with genetic algorithms (GAs). Total project cost is reduced by 1.68% and total construction time is reduced by 8.47%.
(Essam, 2023) conducted a literature review to assess the potential of integrating BIM and optimization methods to schedule construction activities in the most efficient way possible within time and allocated resources. It is highlighted that GAs are considered a proper meta-heuristic alternative for identifying optimal solutions.
(Alothaimeen, 2023) integrated BIM and GAs trying to provide the optimal solution measured in terms of life-cycle cost and sustainability.
This paper proposes an active BIM tool using an optimization system based on GAs. The system identifies for each phase of the repetitive floor cycle the list of elements which must be realized so that it is technically feasible, and at the same time, required work hours during each phase are balanced as much as possible. This balance of work hours leads to a reduced amount of needed human and formwork resources, better safety and working conditions for workers, and decreased waste on the project`s site.

2. METHODOLOGY

The adopted methodology to optimize the cycle plan and the structure of the proposed active BIM tool are presented in figure 4. The optimization system contains mainly two steps. The first step involves the automated generation of constraints for a given BIM model and the construction of a first generation of feasible solutions. The second step consists of the search for optimal solutions using GAs.
Optimization techniques can be classified into two main categories. The first category concerns deterministic algorithms (linear or non-linear programming, enumerative methods, etc.). The second category concerns stochastic algorithms (simulated annealing, genetic algorithms, heuristic methods, etc.). Genetic algorithms are stochastic algorithms adapted to the rapid and global exploitation of a large search space. GAs are selected to optimize repetitive cycle plans for two main reasons: it is suitable for rapid and global exploration of a large space; and it can provide several solutions. Input parameters include unit time values of construction elements used in the BIM model and allocated duration for repetitive floors. Unit time values (needed work hours per unit of measure of a specific construction element) are controlled by the element`s position in the architectural plan, its dimensions, its type, and its shape. Those values could be added to the element`s properties in BIM and they reflect expected labor productivity. They are used to estimate accurately and quickly required working hours for each element through the multiplication of the element`s size by its related unit time. Moreover, the allocated duration for repetitive floor needs to be provided so that the total number of repetitive floor construction phases is identified. By checking the location of construction elements (walls, beams, columns, and slabs), the system automatically generates technical constraints. According to the adopted construction mode (cast-in-situ works, prefabricated works, etc.), a shifting time (lag) between the realization of vertical construction elements (walls, columns, and beams) and horizontal ones (slabs) is envisaged to allow the construction of vertical works in the level i before the realization of the above slab in the level i+1. Also, enough area of slab in level i should be realized to be able to construct vertical works of the level i+1. So, based on the location of vertical elements compared to slab zones, the system generates a range of potential values for the phase (RAP) at which a vertical element could be realized without violating technical constraints related to slabs. Each solution (a cycle) is presented as a chromosome (Figure 5) comprising the m gene (m is the number of construction elements in the repetitive floor).

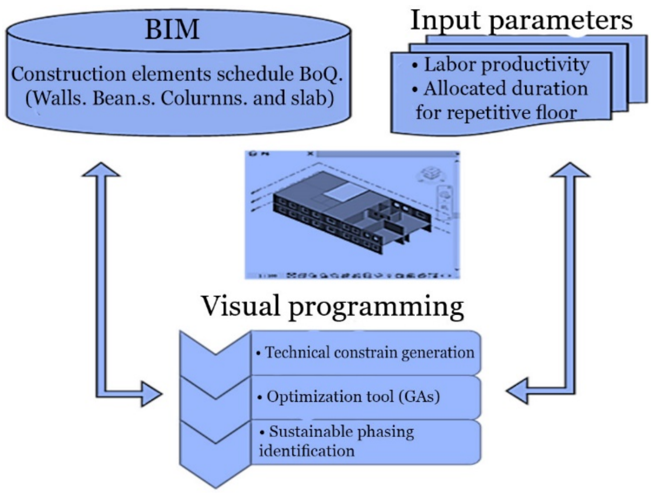

Figure 4: Tool`s structure.

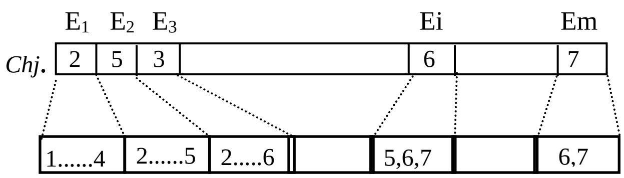

Figure 5: Range of acceptable phase number (RAP).

So, each chromosome is presented like a vector:

$$\overrightarrow{Ch_j} = [E_i]_{i=1}^{m} \;\forall\; E_i = r \quad r \in [1,2,3,\dots,n] \qquad (1)$$

n = allocated duration for the construction of the repetitive floor.
E_i = represents the gene within the chromosome that is part of the solution cycle.
Parameters which control RAP values are: lag value between vertical and horizontal elements; needed duration to construct a slab zone; and workflow direction in the repetitive floor (Istanbullu, 2022)
Two main criteria are used to assess cycle performance:
1- Balance quantities of needed work hours during each phase of the cycle leading to better labour working conditions.
2- Maximizing formwork usage rate leads to more sustainable solutions through minimizing materials waste, increasing profitability performance, and reducing formwork oil consumption.
The performance of each feasible (technically) solution is calculated based on the following function:

$$F = \sum \propto_k * F(j)_k \qquad (2)$$

$\propto_k$ represents the weight (importance) of the criteria k. and F represents the performance function of each feasible (technically) solution. Equations for criteria 1 and criteria 2 are presented below:

$$F(j)_1 = \sum_{r=1}^{n} \frac{|t_m - Cj(r,j)|}{t_m} \qquad (3)$$

Cj(r, j) represents the needed work hours to construct elements selected in phase r. t_m represents the average value of phase work hours.

$$F(j)_2 = \sum_{r=1}^{n} \frac{Lb_d(j) - Lb_j(r,j)}{Lb_d(j)} \qquad (4)$$

$Lb_d(j)$ represents the total needed length of vertical formworks. $Lb_j(r,j)$ represents the length of vertical formwork used during phase r.
The optimization algorithm aims to minimize the value of the *F* function.

3. RESULTS AND DISCUSSION

The proposed active BIM tool was used to generate the repetitive floor construction cycle for real examples. Significant productivity profits from labour and formwork are achieved.
For instance, the proposed tool is used to generate repetitive floor construction cycles for 70 flats building projects. The allocated duration for each floor was 10 days. A 10-phase cycle generated manually by an expert engineer (Manual solution) was compared to two optimized cycle solutions adopting different weight values of the optimization function. In the first optimized solution (G.S. 1) higher weight has been allocated to the first criteria. However, higher weight has been allocated to the second criterion in the optimized solution (G.S. 2). Workhours quantities and non-used formworks amount in each phase related to the manual solution are presented in Table 1.

Table 1: Quantities in each phase in the manual solution

The phase r of cycle	Cj(r,j) [hours]	Non-used Formwork [meter]
1	85	4.8
2	56.05	9.7
3	80.8	4
4	78.05	4.2
5	84.95	3
6	83.6	6
7	65.45	3.3
8	89.55	2.7
9	73.05	5.7
10	42.7	17.5
Max./total	89.55	60.9

It is clearly stated that 89.55 working hours are required in phase 8. While just 42.7 working hours are required in phase 10. These unbalanced quantities negatively impact the productivity and profitability of used construction resources. Considering technical constraints and the large search space, site engineers were satisfied with one feasible solution without a real possibility of optimization.Table 2 shows quantities and non-used formworks in each phase related to optimized solution G.S. 1. And Table 3 shows quantities and non-used formworks in each phase related to optimized solution G.S. 2 Comparing the manual solution to optimized ones, Tables 2 and 3 clearly show better-balanced quantities of work hours and lower values of non-used formworks on the building site. Therefore, at least 10% of labour resources and 25% of non-used formworks could be saved.

Table 2: Quantities in each phase in G.S. 1.

The phase r of cycle	*Cj(r,j)* [hours]	Non-used Formwork [meter]
1	71.4	5.9
2	78.75	2.3
3	73.9	5
4	76.8	1.4
5	78.25	3.4
6	76.15	2.6
7	73.9	3.7
8	72.55	7
9	67	6.7
10	67.6	7.4
Max./total	78.75	45.4

Table 3: Quantities in each phase in G.S. 2

The phase r of cycle	*Cj(r,j)* [hours]	Non-used Formwork [meter]
1	74.15	0.6
2	71.5	0
3	73.15	2.1
4	71.4	0
5	78.1	1.8
6	71	1.5
7	80.6	1.8
8	74.25	0
9	75.1	0
10	65.7	3.9
Max./total	80.6	11.7

4. CONCLUSION

The validity of the presented results is substantiated by multiple examples from real construction sites that have been analyzed in this study. On average, it is reasonable to expect a reduction of around 10% of labour resources and 25% of non-used formwork. Generally, the proposed tool leads to better economic efficiency (one of the three objectives of sustainable development). At the same time, working conditions and safety of labour are much better since work hours quantities are balanced. Only the environmental objectives have not been quantified for the moment. It concerns the reduction of needed formworks and related used oil quantity. It is in this sense that a "sustainable building production" is desired based on the optimization carried out.

Several input parameters can still be analyzed to improve the performance of the proposed tool, specifically, those parameters related to the assessment function. Moreover, the impact on the total project`s cost could be considered. Considering changed site conditions and the uncertainty of using human and material resources, the cycle plan must be reviewed and regenerated from time to time. Advanced technologies like the Internet of Things (IoT), 3D printing, and robotics could be integrated into our tool, and they represent a high potential for future work and development.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FUNDING

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