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BIM-Based Multi-objective Optimization of Framed Structures Considering Carbon Emissions, Construction Cost, and Project Duration

A. Vamsi[1], G. Siva Subramanyam[1], G. Abhith[1], G. Jahnavi[1]

[1]Civil Engineering Department, GMRIT Deemed to be University, GMR Nagar, Rajam, Andhra Pradesh, India-532127

ABSTRACT :

Decisions about a reinforced frame are usually checked one objective at a time. The frame is analysed for safety first quantities and cost come later and embodied carbon and construction time are often looked at only after the design is frozen when changes are expensive. This paper describes a BIM-based workflow that places cost, embodied carbon and construction duration side by side for the set of design alternatives with structural safety treated as a pass-or-fail condition and not as a fourth objective. The case study is a G+8 frame at Visakhapatnam. The frame was modelled in Autodesk Revit, analysed in STAAD.Pro assessed for life-cycle carbon in One Click LCA and sequenced in Autodesk Navisworks Manage TimeLiner while Microsoft Excel carries the quantity, cost, carbon and time calculations. Four structural variants were prepared by changing the slab thickness by 13.3 %. The member sections by 11.1 % to 16.7 %. A preliminary One Click LCA run gave 640 tonnes CO_2e with the product stage (A1–A3) contributing 91.4 % and the Navisworks 4D simulation of the planned construction sequence runs to Day 154 (Week 22) with the fourteen itemised tasks covering the 93 days. Load definition, code checks, quantity take-off and costing are still, in progress. No saving and no optimum design is claimed here. The paper offers the workflow the evidence collected far and a clear statement of the data needed before a preferred design can be selected.

Keywords: BIM, Multi-objective Optimization, Embodied Carbon, Construction Cost, 4D Scheduling, Navisworks

INTRODUCTION

Building Information Modelling or BIM is a way of storing a building as a collection of objects. Each object has geometry and data—things like material, size and type. Drawings, schedules and material quantities all come from the model. So when a change is made in one place it shows up everywhere. In real projects BIM is often used for just one task. A review of 26 case studies by Hartmann et al. (2008) Showed that most projects used 3D and 4D models for one purpose. The authors said more work is needed to bring these models into project activities.

The way of designing a reinforced cement concrete or RCC frame follows a set order. First the layout is chosen. Then the sizes of beams and slabs are guessed. Next the frame is analysed. After that the sizes are changed again and again until the design meets strength and serviceability requirements. After that do people work out quantities, costs and the construction plan. These tasks are often done separately. Different people handle different parts. If a slab thickness changes or a beam size is adjusted each of those files must be updated by hand. That is slow makes mistakes likely and makes it hard to test than a few design options.

Timing is also important. Basbagill et al. (2013) Showed that early decisions on materials and dimensions can significantly reduce the embodied impact.. Designers often delay these decisions. The embodied carbon in an RCC building mostly comes from cement and steel. Once the structure is built most of that carbon is already locked in. A workflow that allows testing of design changes against cost, carbon and time all at once would be very helpful—especially for the repetitive multi-storey RCC frames that are common in residential construction in India.

The goals can conflict. Eleftheriadis et al. (2017) Found that the floor system that was cheapest cost-wise was 3% cheaper than the one that was best for carbon but it had about 7% more carbon. A later study at the building level showed that lifecycle carbon could vary by than 50% while cost varied by only about 10% between optimised designs (Eleftheriadis et al., 2018d). Looking at cost can hide a big carbon cost.. Neither cost nor carbon tells you how long the building will take to construct.

This paper introduces a BIM-based workflow for comparing designs of a multi-storey RCC frame. The comparison looks at cost, embodied carbon and construction time together. It uses one set of quantities and clear assumptions. The goals are:

1. To build and verify the BIM and analytical model of a G+8 RCC frame;
2. To define a set of alternatives and explain how to check their feasibility;
3. To get an estimate of embodied carbon and a 4D construction schedule from the same model;
4. To describe how feasible alternatives will be compared using -dominance screening.

It should be said clearly: this is a work, in progress. The BIM model, four variants, a preliminary carbon result and a construction schedule are ready.. The structural analysis results quantity take-off and cost estimates are not yet done. The paper is written with this limitation in mind.

REVIEW OF WORK

BIM-based cost and carbon optimisation. Eleftheriadis and co-authors have published a series of studies on RC structures. The BIM-based cost and carbon optimisation approach couples finite element modelling with a genetic algorithm and constructability constraints and was tested on real buildings (Eleftheriadis et al., 2018b, 2018c). Eleftheriadis and co-authors discovered that structural layout and slab thickness are among the influential parameters and that floor concrete contributes the largest share to both cost and carbon (Eleftheriadis et al., 2017). Eleftheriadis and co-authors' doctoral work integrates these pieces into a decision framework that uses NSGA-II and TOPSIS ranking (Eleftheriadis, 2018a).

BIM-based life cycle assessment. Basbagill et al. (2013) Linked LCA to BIM design decisions. Used sensitivity analysis to reveal which decisions matter most. Abouhamad and Abu-Hamd (2021) created a BIM–LCA framework for RCC, hot-rolled steel and light steel systems. Demonstrated that the choice of construction system significantly alters embodied energy.

Multi-objective. 4D BIM. NSGA-II (Deb et al., 2002) is the evolutionary approach for locating a set of non-dominated solutions when objectives clash and it is suitable for large design spaces where each evaluation can be automated. Work on 4D BIM by contrast is mainly descriptive (Hartmann et al., 2008).

Two gaps stand out from these studies. First construction duration extracted from a 4D schedule rarely appears as an objective alongside cost and carbon; constructability is addressed through constraints, which's not the same as time. Second none of these studies reports a residential frame. The present work takes a step toward both gaps. These comments apply to the papers we reviewed and should not be taken as a statement, about the entire literature.

CASE STUDY

The building is a RCC moment-resisting frame located in Visakhapatnam, Andhra Pradesh. The project specification calls for a G+8 configuration with each storey having a height of 3.2 metres a plan area of 18 metres by 15 metres a slab of 150 millimetres M30 concrete and Fe500D reinforcement. In the Revit model the grid consists of five lines and four horizontal lines. A column and an isolated footing are placed at every intersection resulting in 20 footings. The model contains nine levels ranging from 0 to 25.60 metres, which matches the 3.2-metre storey height (Fig. 1).

The grid also permits a verification of the element count. Each storey contains 20 columns. The beams span four bays along each of the four grid lines and three bays along each of the five vertical lines leading to 31 beam segments on each floor. Additionally the grid encloses 12 slab panels per floor. If all eight floors above the foundation are framed identically the frame will comprise 160 column segments, 248 beam segments and 96 slab panels. These numbers assume a column at every intersection and a beam on every grid segment. They must be confirmed against the Revit schedules. The plan size of 18 metres, by 15 metres still requires confirmation by adding dimensioned grids to the plan views.

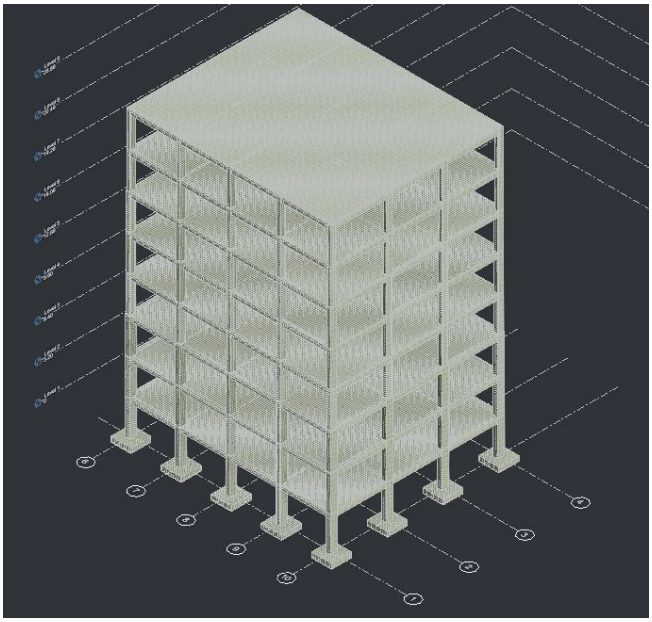


Fig. 1. Revit structural model, 3D view with levels

METHODOLOGY

Workflow and tools

The work follows nine steps: (1) create the baseline BIM and analytical model; (2) apply loads, supports and code-based analysis settings; (3) analyze in STAAD.Pro and verify the outputs; (4) extract responses and quantities; (5) calculate cost, embodied carbon and construction time; (6) generate controlled alternatives; (7) reject alternatives that fail feasibility; (8) compare the alternatives; and (9) present the comparison. Steps 1 and 6 are complete or preliminary step 5 is partly done (carbon and schedule cost pending) and the remaining steps are planned.

Revit supplies geometry, grids, levels, element properties and schedules. STAAD.Pro (2023) supplies the analysis. Navisworks Manage (2024) with TimeLiner links construction tasks to model elements. Plays the sequence as a 4D simulation. One Click LCA supplies the life-cycle carbon result and Excel supplies the quantity, cost, carbon and time calculations. No automatic exchange between these tools is assumed; each link is by file export or manual re-entry.

Alternatives

Four STAAD.Pro models were prepared (Fig. 2). Model 1 is the baseline and Models 2 3 and 4 modify the slab thickness and some of the rectangular section sets. Table 1 lists the five section properties used in each model. Dimensions are, in metres as displayed by the software, which does not indicate which dimension is the depth and which is the width.

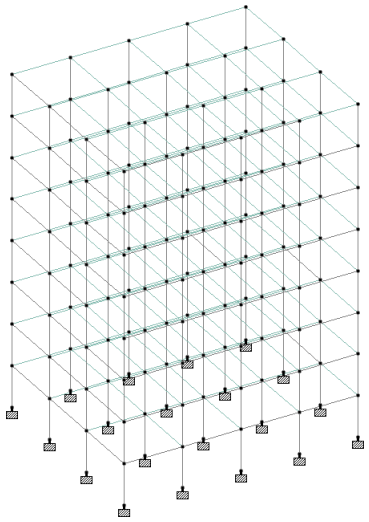


Fig. 2. STAAD.Pro 3D wireframe of the multi-storey frame

The change in each property relative to Model 1 is expressed as a percentage of the baseline value:

$\Delta k = (f_{alt} - f_{base}) / f_{base} \times 100\ \%$ (1)

Models 3 and 4 change both the slab and the member sizes at the time. Because of that it is not possible to see the effect of a change alone.

To make the analysis easier four single-variable alternatives are created from Model 1 by changing one property at a time: S1 (slab thickness reduced from 0.15 to 0.13 m) C1 (R3 dimensions changed from 0.60 × 0.40 to 0.60 × 0.45) C2 (R4 dimensions changed from 0.50 × 0.35 to 0.50 × 0.30) and C3 (R5 dimensions changed from 0.45 × 0.30 to 0.40 × 0.30). Model 3 is made by adding S1 and C1. Model 4 is made by adding S1, C1, C2 and C3 together. Any difference between a combined model and the sum of its changes shows the interaction between those changes.

Structural feasibility

Structural feasibility is treated as a condition than an objective.

A design is considered feasible only if it meets all the checks for strength, stability, deflection, storey drift, minimum size and reinforcement limits set by the Indian Standards IS 456 IS 1893 Part 1. Is 13920.

Before these checks the analysis is verified through equilibrium in which the sum of the support reactions must equal the total applied vertical load:

$\Sigma R_y = \Sigma W$ (2)

Storey drift is screened against the code limit of 0.004 under the design lateral force (BIS, 2016a):

$(u_i - u_{i-1}) / h_i \leq 0.004$ (3)

where u is the displacement at level i and h is the height of storey i.

An alternative that fails any check is dropped whatever its cost or carbon.

The loads – dead, live, wind and seismic for Visakhapatnam –, with the limit-state combinations must be fixed and stated before the results are reported. This is the work that still needs to be completed.

1. BIM-Based Cost Assessment

The construction cost of each design was calculated with Autodesk Navisworks. We measured the quantities of the parts – beams, columns, slabs and foundations – and used those numbers to estimate cost. The same method was used for all designs so that their costs could be compared directly.

2. BIM-Based Embodied Carbon Assessment

The embodied carbon of each design was evaluated with One Click LCA. We matched the amounts and types of material to the environmental data sets. Calculated the Global Warming Potential in CO_2-equivalents. The same settings were used for all designs so that their environmental impacts could be compared.

3. BIM-Based Construction Duration Assessment

The construction time for each design was analysed with Autodesk Navisworks TimeLiner. We linked the BIM components to the planned construction tasks to create a 4-D simulation and show the sequence of work. The overall project time was taken from the schedule. Compared for all designs.

4. Comparative Evaluation of Structural Alternatives

The designs were compared on construction cost, embodied carbon and planned construction time. We put the results together to look at how each design performed environmentally and in terms of time and to pick the best design according to the chosen criteria.

RESULTS AND DISCUSSION

Changes between the structural variants

Calculated using Equation (1) the slab thickness decreases by 13.3 % in Models 3 and 4. In the two models one dimension of the R3 lower-column set increases by 12.5 %. The other dimensions that change decrease by between 11.1
% and 16.7 % as shown in Table 2 and Figure 3.

Table 1. Changes in section properties relative to Model 1

Property changed	Model(s)	Change in dimension (m)	Change (%)
Slab thickness (property 1)	3, 4	0.15 to 0.13	−13.3
R2, common beam set (one dimension)	2	0.30 to 0.25	−16.7
R3, lower columns (one dimension)	3, 4	0.40 to 0.45	+12.5
R4, upper columns (one dimension)	4	0.35 to 0.30	−14.3
R5, perimeter or upper members (one dimension)	4	0.45 to 0.40	−11.1

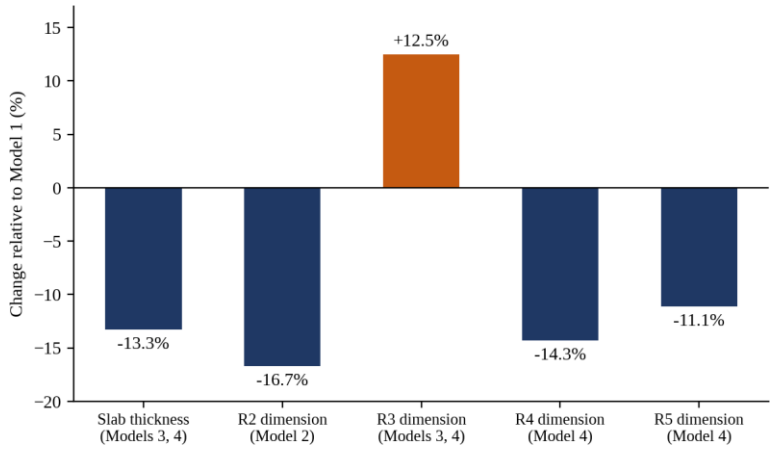


Fig. 3. Change in section dimensions relative to Model 1

These values only describe changes in geometry. If the plan area stays the same the volume of slab concrete is directly proportional to thickness. So the slab concrete volume also drops by 13.3 % in Models 3 and 4. For a member the cross-sectional area depends on the product of its two dimensions.. We cannot yet say how this affects total concrete, steel, cost, carbon or time. The. Length of members carrying each property vary and that must be determined through a quantity take-off.

General principles of reinforced concrete (RCC) design suggest that the impacts will not all go in the direction. A thinner slab reduces self-weight and concrete use. Also reduces stiffness. This means slab deflection and storey drift must be checked. Lower columns increase stiffness and axial capacity but they also increase concrete and steel congestion. Smaller upper columns save concrete where axial load's lower but they reduce capacity and stiffness in those areas. These are expectations based on design logic. They are not conclusions yet. They must be tested by analysis. That is why feasibility needs to be checked before comparing cost, carbon and time.

Preliminary carbon result

The One Click LCA run produced a global warming potential of 640 tonnes CO_2e. The breakdown by life-cycle stage is in Table 3. Figure 4. The product stage A1–A3 accounts for 91.4 % of the total which's typical for a reinforced concrete building where cement and steel production are the main contributors. This matches the findings of Basbagill et al. (2013). It supports focusing on material quantities. The percentages add up to 100.1 % due, to rounding. There was no use-stage (B) module included in this run.

Table 2. Share of global warming potential by life-cycle stage

Stage	Description	Share of GWP (%)
A1–A3	Product stage (materials)	91.4
A5	Construction and installation	5.1
A4	Transport to site	1.9
C2	Waste transport	1.1
C4	Waste disposal	0.6
C3	Waste processing	0.0

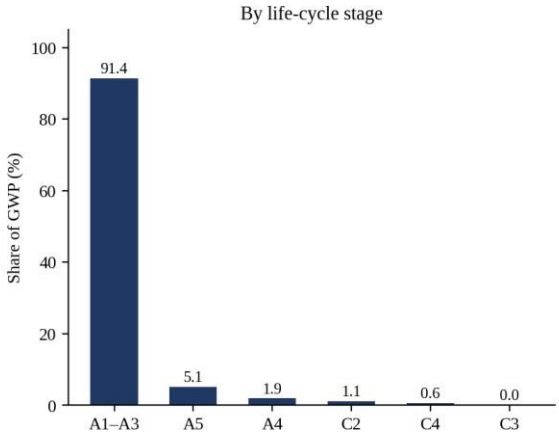


Fig. 4. Share of global warming potential by life-cycle stage (One Click LCA, preliminary run)

This result must be interpreted carefully. We do not consider it as the embodied carbon of the alternatives for four reasons. First the structural model used in the run was not recorded,. Its exact configuration is unknown. Second the gross floor area was not entered, which means the intensity field only shows the total in kilograms. There is no per-metre value and therefore no benchmark class is meaningful. Third the breakdown by element class shows a high share for stairs and ramps and a very low share for the load-bearing frame. This could indicate a mismatch in how quantities were mapped so we have not interpreted the data until it is verified against the Revit quantity schedule. Fourth the breakdown by material—cement, steel and other—was not provided. Because of these issues the 640-tonne figure does not provide a basis for comparison. It is a value only.

Construction schedule

The Time Liner schedule includes fourteen tasks of the type Construct: Footing, Columns 1 to 5 Beams 1 to 4 and Floors 1 to 4. The simulation begins on October 1 2026. As shown in the Simulate tab, in Figure 5 the final frame is March 3 2027. Navisworks reports this as Day 154 and Week 22. The fourteen tasks listed in the task table are scheduled from October 1 2026 to January 1 2027 using calendar days. Table 4 presents a summary of the schedule and Figure 6 shows the sequence of these fourteen tasks.

Table 3. Planned TimeLiner schedule (summary)

Task group	Tasks	Duration (days)
Footing	1	7
Column 1	1	2
Beam 1	1	13
Floor 1	1	7
Columns 2–5	4	7 each (28)
Beams 2–4	3	5 each (15)
Floors 2–4	3	7 each (21)
Subtotal, itemised tasks (to 01-01-2027)	14	93
Remaining period to end of simulation (02-01-2027 to 03-03-2027)	Not itemised	61
Total simulated duration (Day 154, Week 22)	–	154

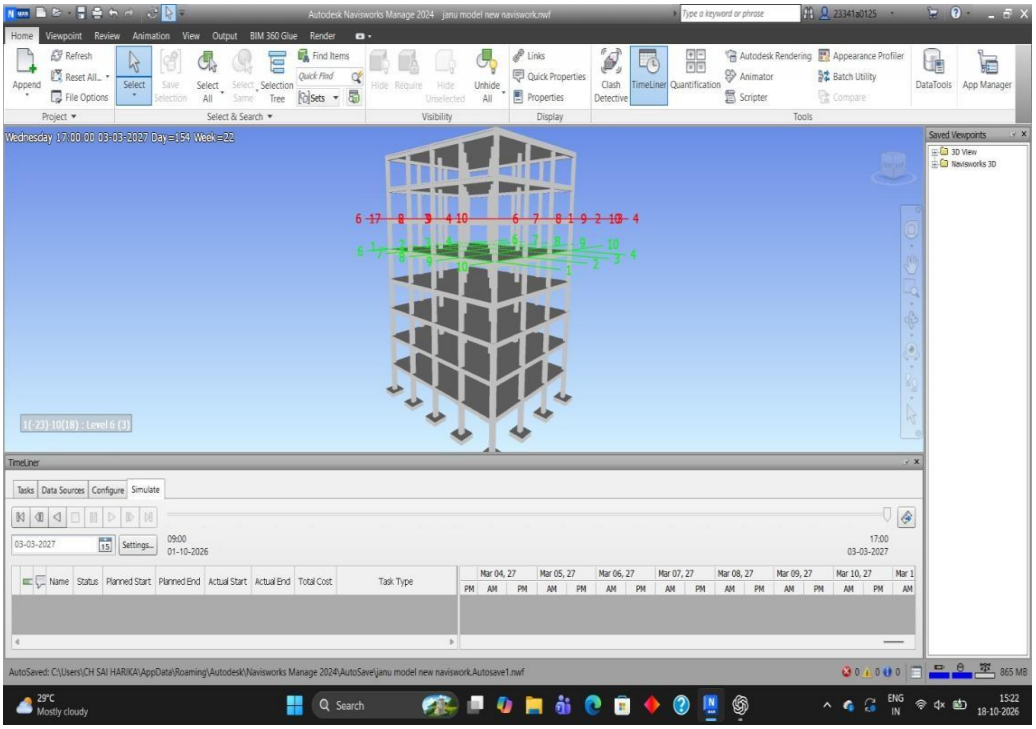


Fig. 5. Navisworks Manage TimeLiner Simulate tab: simulation from 01-10-2026 to 03-03-2027 (Day 154, Week 22)

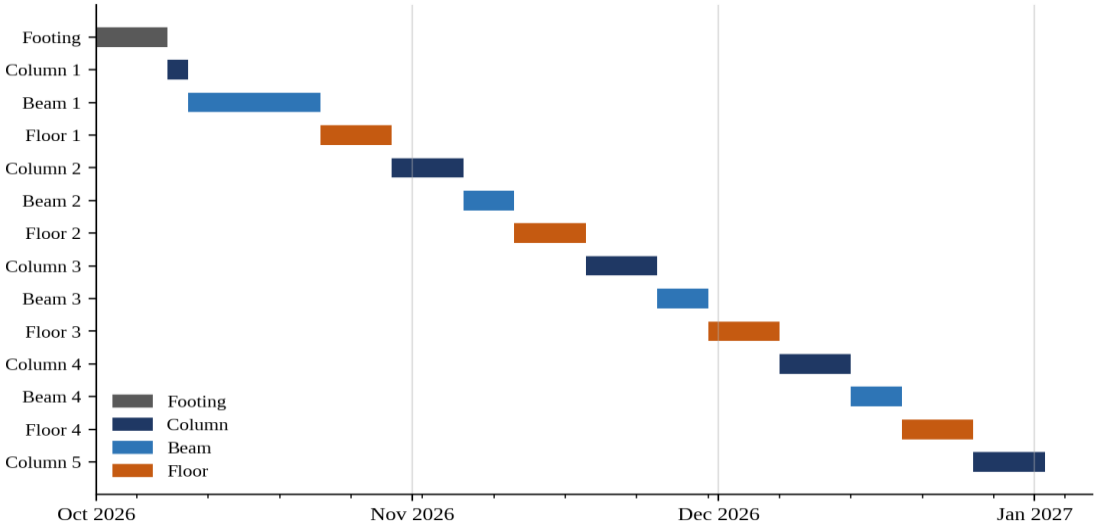


Fig. 6. Planned sequential schedule of the fourteen itemised TimeLiner tasks

For the fourteen tasks the dates go one after another with no breaks and the total time adds up to 93 days. This shows that the plan is completely done in a sequence with no overlapping. Level 1 takes 22 days. Level 1 is in column 2 beam 13 floor 7. Levels 2, 3 and 4 each take 19 days. These are in column 7 beam 5 floor 7. The first long cycle happens because Beam 1 takes 13 days. The total project time is the sum of the task times. So if one task changes the total changes by the amount. For instance if each of Beams 2 to 4 is shortened by one day the plan goes from 93 days to 90 days. This just explains how the sequence works and is not a forecast.

The current times were put in by the project team. They were not based on quantities and productivity from Equation (6). So they can't yet show how a thinner slab or a smaller beam would affect the building time. The simulation goes 61 days past the listed task, which is Day 93 up to Day 154. The tasks that fill this time which are probably for the levels of the nine-level frame are not listed in the task views here. These need to be added to Table 4 before any time comparison is done. The 154-day number should be seen as the planned time for the whole simulation not as something calculated from quantities. To compare time between options each option needs its own schedule made from its own take-off with clear productivity, crew sizes, curing and striking times. In reality work on floors can overlap, so an overlap case should be run next to the strictly sequential one.

The comparison of the four options can be completed once these things are ready: a documented load and support definition with analysis results and pass or fail for every option; a quantity take-off where concrete, steel and formwork are counted by one rule; unit rates and emission factors with sources used the same way for all options; and a separate schedule for each option. Once these are, in place the results can go into one table. The options that are

not as good can be. The rest can be reported with their trade-offs. Cost, carbon and time may support options as seen in earlier studies. In that case the choice depends on what the owner values the most.

LIMITATIONS

- The plan size is taken from the specification. Is not yet confirmed from dimensioned views.
- Slab and member changes are mixed in Models 3 and 4 so their individual effects are not separated until the variable alternatives are analysed.
- Loads, load combinations, support types and analysis results are not yet documented,. No structural feasibility is claimed for any alternative.
- The LCA run lacks a stated model and gross floor area and its element classification needs checking.
- The schedule dates are entered values with no stated productivity behind them and the tasks between Day 93 and Day 154 are not yet itemised in the paper.
- The links between the software tools are manual.
- The literature reviewed is limited to nine publications. Should be widened, especially for NSGA-II studies on RC frames and for Indian projects.

CONCLUSION

This paper described a BIM-based workflow in which structural feasibility, material quantities, cost, embodied carbon and construction duration of an RCC frame can be compared for the set of alternatives. For a G+8 frame at Visakhapatnam, the Revit model, four STAAD.Pro variants, a preliminary carbon result of 640 tonnes CO e (product stage 91.4 %) and a Navisworks 4D schedule have been prepared. The simulation runs to Day 154 (Week 22) and its first fourteen itemised tasks, in a sequential order span 93 days. The four variants differ in a way: slab thickness falls by 13.3 % in Models 3 and 4 one lower-column dimension rises by 12.5 % and other member dimensions fall by 11.1 % to 16.7 %.

We do not claim any saving in cost, carbon or time. We do not name a preferred design because the analysis results, quantities and costs needed for that are not yet available. The value of the work at this stage lies in the documented workflow the open points it has exposed and the clear statement of the data a full comparison needs. These can help student teams who want to continue from a defined starting point.

Future work will complete the load definition and code checks extract quantities and cost assess carbon on a structurebasis for each alternative build a schedule for each alternative from stated productivity and apply non-dominance filtering to select the best balanced design. Later extensions could include automated data exchange between Revit and STAAD.Pro a model that updates everything from one change, regional carbon data for Indian cement and steel sensitivity analysis on rates and emission factors and evolutionary optimisation with NSGA-II once evaluation is automated.

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