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Mixed-Integer Nonlinear Programming for Multi-Floor EFB Biodiesel Plant Layout Optimization: Balancing Economics, Safety, and Structural Constraint

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Abstract

Designing multi-floor arrangements for biodiesel production facilities that utilize empty fruit bunch (EFB) feedstock represents a computationally intensive, large-scale problem that requires the concurrent assessment of cost, hazard mitigation, and building integrity constraints. The present work proposes a Mixed-Integer Nonlinear Programming (MINLP) formulation tailored to multi-level plant layouts, jointly determining optimal equipment materials, vertical floor allocations, sectional positioning, and passive safeguarding features based on explicit safety quantification. Developed within the General Algebraic Modeling System (GAMS) environment, the model is tackled through a staged decomposition consisting of three sequential phases—(i) choice of construction materials together with load-bearing evaluation, (ii) intra-section multi-floor arrangement, and (iii) full-plant sectional coordination—because solving the full monolithic MINLP violates academic solver license restrictions and does not reach convergence under realistic time constraints. In contrast, the sequential procedure consistently delivers solutions featuring small optimality gaps (overall CPU usage: 22.97 min). Applied to a 1,000 t/d EFB processing scenario involving 57 equipment units distributed across seven functional sections, the resulting layout achieves a 28.9% reduction in total capital expenditure, a 51.97% decrease in required land area, and—when separations follow Dow's Fire and Explosion Index (F&EI) guidelines including credit for installed devices—a 18.8% drop in Maximum Probable Property Damage (MPPD) before protective measures and a 69.0% reduction once protection is accounted for. This hierarchical decomposition technique shows that highly complex facility layout tasks incorporating formal safety limits can be addressed in a tractable and effective manner, supplying a generalizable methodology suitable for diverse multi-objective design problems encountered in the chemical processing and renewable energy domains.

Keywords Optimization, General algebraic modeling system, Aspen Plus, Process simulation, Dow fire and explosion index, Palm empty fruit bunch

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Introduction

Balancing the pursuit of net-zero emissions goals with the need for a reliable energy supply continues to drive strong demand for scalable, lower-carbon liquid fuels within the chemical and transportation fuel industries. Among viable renewable pathways, biodiesel, together with diesel-range biofuels derived from lignocellulosic waste streams, has maintained significant research and industrial interest owing to its ability to leverage established petroleum refining and distribution systems while providing prompt reductions in full life-cycle greenhouse gas emissions upon blending with conventional diesel [1]. In the palm oil production chain across Southeast Asia, empty fruit bunch (EFB)—the

lignocellulosic fibrous material discarded after fruit extraction—stands out as an especially valuable non-edible biomass resource. Contemporary techno-economic assessments and systems-level investigations increasingly portray EFB as a widely available yet largely unexploited residue offering major opportunities for transformation into fuels and chemical products [2–4]. Notably, Malaysia produced an average of 22.42 million tonnes of EFB each year between 2017 and 2019, underscoring the considerable resource volume that could be harnessed through carefully planned collection, transport, and facility placement strategies [2]. Complementing its abundance, emerging conversion research indicates that EFB lends itself effectively to thermochemical processing routes yielding bio-oils that serve either as intermediates for diesel-range molecules or as performance-enhancing additives in biodiesel blends: hydrothermal liquefaction (HTL) applied to lignin fractions isolated from EFB produces phenolic-rich bio-oils suitable for antioxidant use in biodiesel formulations [5], and direct HTL of unseparated EFB in the presence of aqueous ethanol co-solvent has demonstrated biocrude yields reaching 40.8 wt% at 275 °C in small-scale reactors, thereby supplying dependable yield and quality targets for subsequent refining steps [6]. At the same time, studies focused on waste valorization consistently emphasize that geographic and temporal feedstock availability, along with handling difficulties, exert decisive influence over project viability and operating expenses: analyses of wood-residue-to-biofuel chains, for instance, show profitability declining sharply when collection radii exceed around 80 km or when feedstock moisture surpasses roughly 60%—underscoring the tight linkage between feedstock sourcing decisions and the detailed engineering of the conversion facility itself [7]. These converging lines of evidence call for renewed scrutiny of layout optimization strategies specifically tailored to EFB-based biodiesel or diesel-range biofuel plants, with the explicit aim of satisfying economic, operational, and safety objectives in an integrated manner.

At its core, the layout optimization problem for process plants is fundamentally multi-dimensional and trade-off intensive: capital outlays for piping networks and pumps, expenses related to land acquisition and multi-story construction, mandated safety buffer zones, choices of corrosion-resistant materials, requirements for efficient solids conveying, and installation of protective barriers all interact in intricate and frequently opposing fashions; cost-cutting measures in one area can inadvertently elevate risk profiles in another [8–11]. Within facilities that process multi-phase flows typical of biodiesel production—pretreatment slurries, reactive liquid mixtures, phase-separating operations, and vapor-liquid contacting units—both spatial configuration and vertical positioning become especially consequential: differences in elevation directly impact required pumping power and available Net Positive Suction Head (NPSH), while the relative placement and grouping of sections strongly influence emergency egress paths and the potential for propagating (domino) accident scenarios [9–11]. Research concerning industrial site selection additionally reveals that, under combined environmental, societal, and financial evaluation criteria enforced through GIS-supported multi-criteria decision analysis (MCDM), only an extremely limited portion of candidate parcels usually qualifies as appropriate; a recent 2024 investigation into urban waste-to-energy facility placement that employed AHP and fuzzy-AHP methodologies integrated with weighted-overlay GIS techniques, for example, classified approximately just 0.04% of the evaluated region as “very suitable,” thereby illustrating how stringent upstream location constraints severely restrict the allowable design freedom within the chosen plot and consequently heighten the practical importance of advanced intra-site layout optimization [12]. In a parallel vein, findings reported by Wijitkosum *et al.* [13] from pyrolysis-based valorization work affirm realistic processing conditions (such as 450–500 °C for producing biochar from bamboo chopsticks) and resulting product characteristics that favor the adoption of compact, highly integrated plant designs in which material flow logistics and spatial organization must be deliberately aligned with core process parameters [13]. When viewed together, this chain of interdependent choices—spanning feedstock siting, supply-chain logistics, and internal facility layout—demands a mathematically rigorous, solver-compatible optimization approach capable of incorporating elevation-dependent phenomena, realistic land-area limitations, and numerically defined safety performance metrics.

Mathematical optimization techniques for facility layout have evolved significantly, progressing from initial single-level Mixed-Integer Linear Programming (MILP) frameworks to more advanced continuous-domain and multi-level configurations. MILP continues to offer advantages whenever cost and distance relationships can be effectively linearized; however, numerous real-world restrictions—such as hydraulic head and power requirements, nonlinear proxies for risk, and the performance of protective devices—are better captured through Mixed-Integer Nonlinear Programming (MINLP). Contemporary investigations have developed multi-criteria models that link overall financial expenditure with

built-in safety indicators (e.g., Dow's Fire & Explosion Index (F&EI)) to produce plant arrangements that are both economically viable and compliant with safety standards [8, 9, 14]. Further developments incorporate considerations of domino-effect hazards through specialized indices or scenario-driven escalation analyses, along with the deliberate positioning and dimensioning of passive protective elements [10, 15]. A key insight from multi-floor optimization in continuous spatial settings—with explicit floor allocation and non-overlapping restrictions—is that vertical positioning choices can substantially alter the cost–risk trade-off frontier compared to single-floor designs; elevation-based separation often serves as an efficient alternative to horizontal sprawl for mitigating propagation risks while avoiding high land expenses [8, 11]. Building on these developments, Sukpancharoen *et al.* [16] present a comprehensive multi-objective MINLP approach for process plant layout that harmonizes cost performance and safety across petrochemical, food, and polymer applications, revealing that well-integrated safety requirements can actually decrease overall expenses and thereby establishing a relevant methodological benchmark for the cost–risk integration strategy employed here.

In parallel with cost-driven layout research, another line of inquiry embeds measurable safety parameters more explicitly into the optimization process. Although Dow's F&EI continues to be the predominant index-based proxy, its emphasis on comparative fire and explosion hazards has spurred the creation of supplementary metrics and economic valuation methods; notably, Dow's F&EI framework quantifies potential accident-related financial losses, allowing damage and loss terms to be incorporated consistently either in the objective function or as binding constraints [17]. From an occupational and process safety standpoint, inherently safer design (ISD) concepts should extend beyond individual unit operations to encompass entire plant layouts—for instance, through deliberate segregation, inventory reduction by inherent means, and siting strategies resistant to escalation—so that ISD principles remain effective rather than being undermined during final plot arrangement [18]. Moving beyond index-based approaches, risk-aware multi-objective layout optimization tailored to biodiesel-type facilities gains from modeling equipment susceptibility under uncertainty; mixed-integer models leveraging equipment vulnerability indices (EVI) have achieved reductions in domino-event probabilities through data-guided reconfigurations [19]. Significantly, research that simultaneously optimizes passive safeguards (such as blast barriers and water deluge installations) alongside layout configuration shows that these measures can reduce overall anticipated costs when escalation consequences are properly monetized [15]. Collectively, these findings reposition safety from a peripheral restriction to a central driver of optimal plant configurations [9, 15, 17–19].

Outside the narrow scope of layout design, broader process synthesis literature illustrates the power of MINLP within superstructure optimization and holistic design under combined cost–risk considerations, where spatial organization remains closely intertwined with the process flowsheet. Applications in subsea processing and other space-constrained facilities highlight the successful inclusion of nonconvex physical relationships (e.g., flow deliverability, pressure dependencies, multi-phase pumping) together with reliability and maintenance factors, with solutions approaching global optimality within practical industrial computing limits and thereby indicating circumstances in which deterministic global solvers outperform local outer-approximation MINLP algorithms [20]. For facilities of substantial scale, decomposition techniques and solver-tailored procedures (such as progressive problem reduction or multi-directional probing) have become essential to maintain reasonable runtimes while preserving accurate representation of multiple floors, zoned areas, tall vessels, and interconnection details [11]. In implementation, the chosen modeling platform must effectively handle mixed discrete–continuous features and seamlessly connect to both local and global MINLP solvers; the General Algebraic Modeling System (GAMS) fulfills these requirements and enjoys widespread use for constructing multi-objective MILP/MINLP formulations, invoking outer-approximation or spatial branch-and-bound algorithms, and orchestrating layered solution methodologies [11, 17, 20].

Notwithstanding these advancements, three critical shortcomings persist in facilities converting empty fruit bunch (EFB) into biodiesel. First, current layout optimization models seldom combine (i) material choices governed by corrosion and hazard exposure, (ii) continuous-space multi-floor allocation decisions, and (iii) explicit safety quantification (via Dow's F&EI and domino metrics) together with simultaneous optimization of protective devices within one unified MINLP. Second, joint optimization of passive protection systems and spatial arrangement remains infrequent; when pursued, it is typically separated from vertical floor decisions or addressed through heuristic simplification [10, 15, 19]. Third, detailed EFB-specific case applications remain scarce despite accumulating knowledge of conversion efficiencies and location-

related limitations [2, 5, 6]. The current study fills these voids by developing a computationally tractable, multi-objective MINLP model in GAMS that (i) integrates material selection with risk-index-constrained safety requirements; (ii) concurrently optimizes multi-floor layout alongside economic factors (piping, pumping, land, and civil works) and safety through protection device sizing and placement; and (iii) applies the framework to a practical EFB-to-biodiesel/bio-oil scenario incorporating sensitivity analyses on HTL yield variations and available site area [8–11, 21, 22]. Situated within the context of integrated layout research demonstrating cost benefits from monetized safety [16] and siting/logistics investigations highlighting restrictive land suitability and transport thresholds [12], this contribution intentionally links siting, logistics, and layout decisions rather than addressing them separately.

The work is guided by four primary objectives: (1) to construct a multi-objective MINLP for multi-floor plant layout that integrates economic and safety objectives while respecting realistic hydraulic behavior and mandated separation distances; (2) to incorporate material selection and passive-protection sizing directly into the layout optimization space; (3) to code and solve the model in GAMS using an expandable three-stage decomposition procedure; and (4) to evaluate the methodology on a realistic EFB-based case employing documented conversion performance data and practical land-area restrictions [2–6, 9–15].

Problem Statement and Case Study Definition

The proposed optimization approach targets the layout design of a 1,000 t/d empty fruit bunch (EFB) biodiesel plant capable of generating 87,000 L/d of gasoline-range product and 148,000 L/d of biodiesel. The plant includes 57 individual equipment items organized into seven interconnected processing sections, as depicted in Figure 1 and detailed in Table 1.

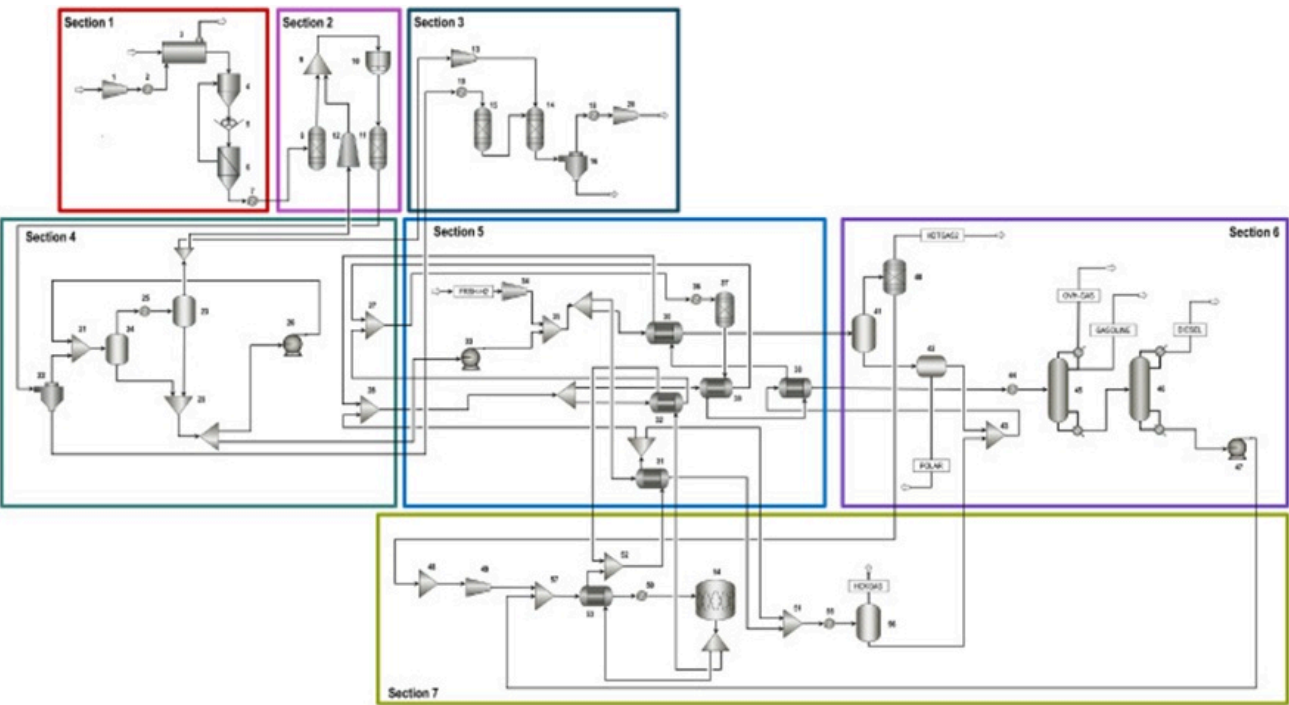


Figure 1. Process flow diagram for the EFB-to-biodiesel case study (7 sections, 57 items).

Table 1. Overview of process sections and primary equipment in the EFB biodiesel case study (S1–S7).

Section	Process function	Major equipment types

S1: Pretreatment	Feedstock preparation (drying, size reduction)	Gyratory crusher, tray dryer, and screen
S2: Pyrolysis	Thermal decomposition (450–500 °C)	Reactors (3), cyclone, and heat exchangers
S3: Combustion	Energy recovery from char/gas	Combustors (2) and cyclone dust collector
S4: Separation	Phase isolation through quenching	Vessels (2), cooler, and cyclone
S5: Hydrotreating	Oxygen removal (< 2% target)	Reactor, H ₂ compressor, and heat exchangers
S6: Distillation	Product fractionation	Distillation columns (2), pumps, and vessels
S7: Hydrocracking	Heavy fraction upgrading	Reactor, separators, and heat exchangers

Figure 2 presents an overview of the three-stage optimization procedure, including representative practical constraints applied at each stage. Stage 1 focuses on material selection (e.g., SS316 versus titanium), which directly influences equipment weight and, in turn, determines structural loading demands. Stage 2 incorporates physical restrictions: no overlap is permitted between equipment items i_1 and i_2 (ensuring a minimum 0.5 m clearance for maintenance), hazardous units are surrounded by circular exclusion zones derived from their Dow's F&EI ratings, and all items must remain confined within their assigned section perimeters. Stage 3 positions the seven sections without spatial overlap while minimizing the lengths of interconnecting piping runs.

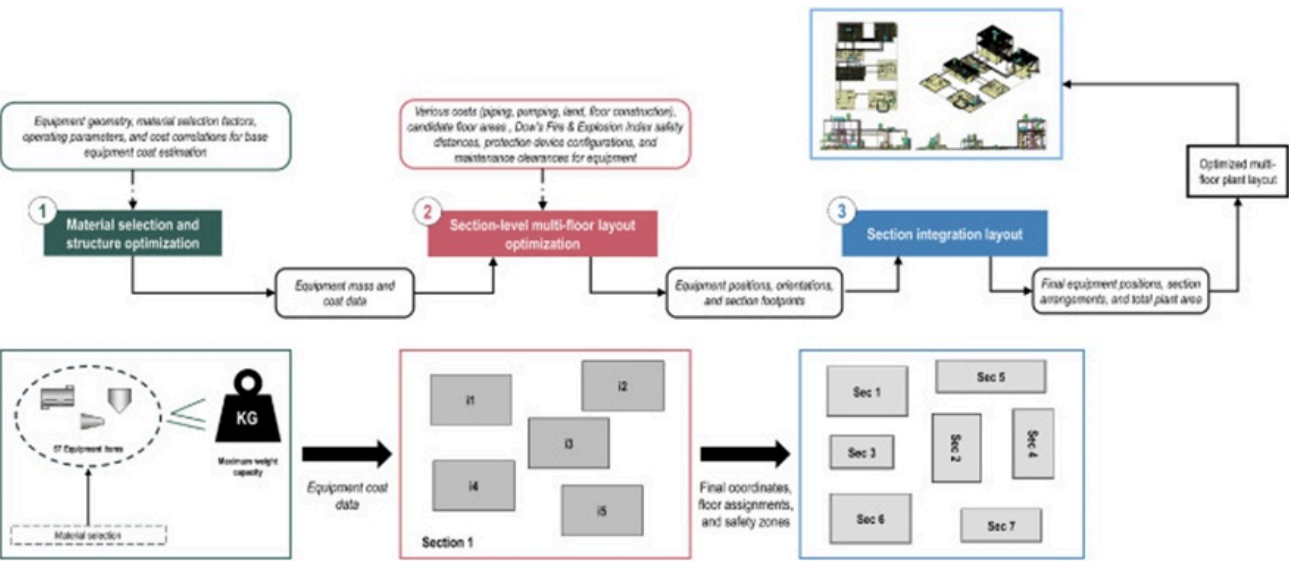


Figure 2. Schematic of the three-stage optimization structure: Model 1 (material and structural choices), Model 2 (section-level multi-floor layout incorporating Dow's F&EI), Model 3 (overall plant-wide section coordination).

Computing environment and software

The entire optimization framework was developed and executed in GAMS Studio 34.0 (under Academic License) using the DICOPT solver on a workstation equipped with an Intel® Core™ i9–13900KF processor (3.00 GHz base clock, 32 GB RAM). Input equipment specifications were derived from simulations performed in Aspen Plus v8.8, while the resulting layouts were rendered and inspected using AutoCAD Plant 3D 2019.

By adopting the decomposition strategy, the method ensures computational feasibility while retaining essential linkages across stages; each subproblem involves 500–2,000 variables, compared with the monolithic model, which exceeds 8,500 variables.

Mathematical Formulation

Model 1 — material selection and structural type assignment

As outlined in the three-step objective structure shown in [Figure 2](#), the initial mathematical component addresses the selection of equipment materials. Model 1 comprises constraints related to equipment mass, section-level total mass, and equipment acquisition costs.

Mass of equipment constraints

Each equipment item must be assigned exactly one material type ([Eq. 1](#)):

$$\sum_{te} zz_{i,te} = 1 \quad \forall i \quad (1)$$

Where the binary variable $zz_{i,te}$ equals 1 if material te is chosen for equipment i , and 0 otherwise.

The unladen mass of equipment item i is computed via [Eq. 2](#).

$$mass_i = \sum_{te} p_{te} vol_i zz_{i,te} \quad \forall i \quad (2)$$

Mass of sections constraints

The aggregate mass of each section is obtained by summing the masses of its constituent equipment items plus the material hold-up (inventory load) within those items ([Eq. 3](#)), where $mass_{fi}$ represents a parameter reflecting the maximum hold-up capacity of each item.

$$Tm_{sec} = \sum_i mass_i + \sum_i mass_{fi} \quad \forall i : group_{i,sec} = 1 \quad (3)$$

An upper limit on the total mass per section is enforced by [Eq. 3](#), accounting for the load-bearing capacity of the selected structural type and a minimum required footprint area ($guess_{sec}$). The binary variables wd_{st} and sec determine the structural type assigned to each section ([Eq. 4](#)).

$$Tm_{sec} \leq \sum_{st} wd_{st,sec} capweight_{st} guess_{sec} \quad \forall sec : group_{i,sec} = 1 \quad (4)$$

Exactly one structural type must be chosen per section ([Eq. 5](#)).

$$\sum_{st} wd_{st,sec} = 1 \quad \forall sec \quad (5)$$

Structural cost parameters were derived from literature [[23](#), [24](#)] for the two options— $st1$ (1,000 kg/m² capacity) and $st2$ (1,500 kg/m² capacity)—and are used to define the structure-related cost term in the objective function ([Eq. 22](#)), in conjunction with the floor load-capacity restrictions imposed by [Eqs. 3-5](#).

Equipment cost constraints

The equipment cost restrictions in Model 1 rely on widely accepted cost-estimation relationships [25] expressed by Eqs. 6-8. These costs are adjusted based on the selected material using dedicated material correction factors. The same binary indicator $z_{i,te}$, already introduced to assign materials in the mass balance section, is used here to select the corresponding material multiplier listed in Table 2 for the equipment item i , in line with the methodology referenced in [26].

$$w_i = \sum_{te} \pi (\alpha_i + tp_i) (hita_i + 0.8\alpha_i) 2.2046tp_i p_{te} z_{i,te} \quad \forall i : HoAndOrr_i = 1 \quad (6)$$

$$cvv_i = \exp(8.9552 - 0.233\ln(w_i) + 0.04333\ln(w_i^2)) \quad \forall i : hor_i = 1 \quad (7)$$

$$cvv_i = \exp(7.0132 + 1.8255\ln(w_i) + 0.02297\ln(w_i^2)) \quad \forall i : orr_i = 1 \quad (8)$$

For pressure vessels and distillation/absorption columns, the reference (bare) cost cvv_i is a function of the equipment's weight w_i , as defined in Eq. 9.

$$cpv_i = \frac{\left(\sum_{te} \frac{z_{i,te} (fm_{te,typ} cvv_i + cpl_i) 500}{550} \right)}{10^5} \quad \forall i, typ : HoAndOrr_i, fm_{te,typ} \geq 1, typ = 5 \quad (9)$$

$$\sum_{te} z_{i,te} fm_{te,typ} / fm_{te,typ} = 1 \quad \forall i, typ : HoAndOrr_i, fm_{te,typ} \geq 1, typ = 5 \quad (10)$$

Table 2. Material-specific cost adjustment factors categorized by equipment type in Model 1.

Types of material	typ1	typ2	typ3	typ4	typ5
te1	1			1.7	1.7
te2	2	2.5	3	1.7	1.7
te3	3.5	5	1.2		5.4
te4	9.7		2.6		7.7
te5			1.1		2.1
te6					1
te7					1.7

Note: typ1 = pump, typ2 = compressor, typ3 = heat exchanger, typ4 = heater, typ5 = vessel. te1 = cast iron, te2 = stainless steel, te3 = nickel, te4 = titanium, te5 = stainless steel 316, te6 = carbon steel, te7 = stainless steel 304.

To enforce the selection of precisely one material when determining vessel cost CPVI, Eq. 10 is combined with Eq. 9. An identical single-choice logic is applied consistently to the cost computations for all other equipment categories.

$$cpf_i = \frac{\left(\sum_{te} \frac{fp_i fm_{te,typ} cbf_i zz_{i,te}^{550}}{500} \right)}{10^5} \quad \forall i, typ : heater_i, fm_{te,typ} \geq 1, typ = 4 \quad (11)$$

$$\sum_{te} zz_{i,te} fm_{te,typ} / fm_{te,typ} = 1 \quad \forall i, typ : heater_i, fm_{te,typ} \geq 1, typ = 4 \quad (12)$$

Fired heater cost for item i is represented by cpf_i (Eq. 11).

$$cpt_i = cpv_i + ct_i \quad \forall i : dis_i = 1 \quad (13)$$

The distillation column cost for item i is denoted by cpt_i (Eq. 13).

$$ccomp_i = \frac{\left(\sum_{te} \frac{fd fm_{te,typ} cb_i zz_{i,te}^{550}}{500} \right)}{10^5} \quad \forall i, typ : comp_i, fm_{te,typ} \geq 1, typ = 2 \quad (14)$$

$$\sum_{te} zz_{i,te} fm_{te,typ} / fm_{te,typ} = 1 \quad \forall i, typ : comp_i, fm_{te,typ} \geq 1, typ = 2 \quad (15)$$

Compressor cost for item i appears as $ccomp_i$ (Eqs. 14 and 15).

$$cpp_i = \frac{\left(\sum_{te} \frac{ft fm_{te,typ} cbp_i zz_{i,te}^{550}}{500} \right)}{10^5} \quad \forall i, typ : pump_i, fm_{te,typ} \geq 1, typ = 1 \quad (16)$$

$$\sum_{te} zz_{i,te} fm_{te,typ} / fm_{te,typ} = 1 \quad \forall i, typ : pump_i, fm_{te,typ} \geq 1, typ = 1 \quad (17)$$

Pump cost for item i (motor excluded) is given by cpp_i (Eqs. 16 and 17).

$$cph_i = \frac{\left(\sum_{te} \frac{fp_i fm_{te,typ} cbh_i zz_{i,te}^{550}}{500} \right)}{10^5} \quad \forall i, typ : heatex_i, fm_{te,typ} \geq 1, typ = 3 \quad (18)$$

$$\sum_{te} zz_{i,te} fm_{te,typ} / fm_{te,typ} = 1 \quad \forall i, typ : heatex_i, fm_{te,typ} \geq 1, typ = 3 \quad (19)$$

Heat exchanger cost for item i is expressed as cph_i (Eqs. 18 and 19).

$$cpr_i = \frac{(cpv_i + cpa_i)550}{500} \quad \forall i : reactor_i = 1 \quad (20)$$

Reactor cost for item i is indicated by cpr_i (Eq. 20).

$$cp_i = cpv_i + cpf_i + cpt_i + ccomp_i + cpump_i + cph_i + cpr_i + cps_i + cpd_i + cpc_i + cpg_i \quad \forall i \quad (21)$$

In addition, activation of the appropriate cost equation for each equipment category is regulated by the material factor $fmte, typ$ together with the type code typ , reflecting the permissible materials shown in Table 2. For example, the heat exchanger cost relation in Eq. 18 becomes active only when $typ = 3$ (heat exchanger designation) and $fmte, typ \geq 1$ for the material under consideration. Furthermore, Eq. 18 is restricted to material codes $te2$ (stainless steel), $te3$ (nickel), $te4$ (titanium), and $te5$ (stainless steel 316), since only these satisfy $fmte, typ \geq 1$. Eq. 19 is included specifically to guarantee that exactly one material is assigned to each heat exchanger. Comparable single-material enforcement equations must accompany the remaining cost expressions—Eqs. 9, 11, 14, 16, and 18—to maintain consistency across all equipment types.

Objective function for model 1: material selection

The goal of Model 1 is to minimize the combined cost of equipment procurement and structural support. The objective function, therefore, seeks to reduce the sum of individual equipment costs and the overall structural cost:

$$wei = \sum_i cp_i + \left(\sum_{st, sec} wd_{st, sec} cost_{st} guess_{sec} \right) / 10^5 \quad (22)$$

Where cp_i denotes the cost of equipment item i , and $cost_{st}$ represents the total cost of the structural system.

This formulation constitutes a Mixed-Integer Nonlinear Programming (MINLP) problem that minimizes the objective given by Eq. 22, subject to the constraints expressed in Eqs. 1-21.

Model 2 — section-level multi-floor layout with Dow's F&EI safety integration

Model 2 constitutes the second stage of the optimization procedure illustrated in Figure 2, addressing the multi-floor arrangement of process equipment within each section. It incorporates a comprehensive set of restrictions, including floor allocation rules, equipment orientation specifications, non-overlap requirements, placement distance limitations, safety separation distances derived from Dow's F&EI, boundary limits for the layout domain, and area occupancy constraints.

Floor constraints

Following optimization of Model 1, the maximum allowable weight for each section ($Mmax_{sec}$) is determined by identifying the single heaviest equipment item assigned to that section, using the equipment weights obtained from Model 1 as inputs to Eqs. 23 and 24.

$$Mmax_{sec} = maximum [(mass_i + mass_{f_i}); \quad \forall i : group_{i, sec} = 1] \quad \forall sec \quad (23)$$

$$wax_{i,sec} = 1 \quad \forall i, sec : group_{i,sec} = 1, mass_i + massf_i = Mmax_{sec} \quad (24)$$

Where $wax_{i, sec}$ is a parameter representing the maximum weight contribution of item i when placed in section sec .

The heaviest equipment item i within each section is then mandatorily assigned to the ground (first) floor according to [Eq. 25](#).

$$V_{i,sec,k} \geq \sum_i wax_{i,sec} \quad \forall k, sec : k = 1, group_{i,sec} = 1, mass_i + massf_i = Mmax_{sec} \quad (25)$$

This ground-floor assignment rule for the most massive unit ($Mmax_{sec}$) follows established engineering practice, promoting structural stability, minimizing required pumping head, and facilitating easier maintenance access. The heuristic imposes only a minor penalty on the objective (< 3% impact on total cost) while significantly enhancing constructability and reducing the feasible search space.

All remaining equipment items i whose weight is less than that of the heaviest item in the same section are assigned to exactly one floor level ([Eq. 26](#)).

$$\sum_k V_{i,sec,k} = 1 \quad \forall i, sec : group_{i,sec} = 1, mass_i + massf_i < Mmax_{sec} \quad (26)$$

The binary variable $Z_{i,j,sec}$, which indicates whether equipment items i and j within section sec share the same floor, is defined by [Eqs. 27–29](#):

$$Z_{i,j,sec} \geq V_{i,sec,k} + V_{j,sec,k} - 1 \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (27)$$

$$Z_{i,j,sec} \leq 1 - V_{i,sec,k} + V_{j,sec,k} \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (28)$$

$$Z_{i,j,sec} \leq 1 + V_{i,sec,k} - V_{j,sec,k} \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (29)$$

Where $Z_{i,j,sec} = 1$ if items i and j in section sec are placed on the same floor, and 0 otherwise.

The total number of floors required per section is calculated via [Eq. 30](#).

$$NF_{sec} \geq \sum_k k V_{i,sec,k} \quad \forall i, sec : group_{i,sec} = 1 \quad (30)$$

Equipment orientation constraints

Decisions regarding the orientation of each equipment item i determine its effective length and depth dimensions, as specified in [Eqs. 31–32](#).

$$l_i = \alpha_i O_i + (\beta_i (1 - O_i)) \quad \forall i \quad (31)$$

$$d_i = \alpha_i + \beta_i - l_i \quad \forall i \quad (32)$$

The same orientation logic is extended to account for the additional clearance required for maintenance access around equipment item i , governed by [Eqs. 33–34](#).

$$v_{mainx_i} = mainx_i O_i + (mainy_i (1 - O_i)) \quad \forall i \quad (33)$$

$$v_{mainy_i} = mainx_i + mainy_i - v_{mainx_i} \quad \forall i \quad (34)$$

Non-overlapping constraints

To avoid any two equipment items i and j occupying the same physical space (that is, sharing identical x–y coordinates or having the coordinates of item i fall within the spatial extent of item j), non-overlap restrictions are enforced as follows:

$$x_{i,sec} - x_{j,sec} + M_{sec} (1 - Z_{i,j,sec} + Ea_{i,j} + Eb_{i,j}) \geq 0.5 (l_i + l_j) + (v_{mainx_i} + v_{mainx_j}) \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (35)$$

$$x_{j,sec} - x_{i,sec} + M_{sec} (2 - Z_{i,j,sec} - Ea_{i,j} + Eb_{i,j}) \geq 0.5 (l_i + l_j) + (v_{mainx_i} + v_{mainx_j}) \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (36)$$

$$y_{i,sec} - y_{j,sec} + M_{sec} (2 - Z_{i,j,sec} + Ea_{i,j} - Eb_{i,j}) \geq 0.5 (d_i + d_j) + (v_{mainy_i} + v_{mainy_j}) \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (37)$$

$$y_{j,sec} - y_{i,sec} + M_{sec} (3 - Z_{i,j,sec} - Ea_{i,j} - Eb_{i,j}) \geq 0.5 (d_i + d_j) + (v_{mainy_i} + v_{mainy_j}) \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (38)$$

These restrictions become active exclusively when the two items i and j are assigned to the identical floor level within their section ($Z_{i,j,sec} = 1$). The parameter M_{sec} serves as a sufficiently large upper bound and is computed according to [Eq. 39](#).

$$M_{sec} = \text{maximum} [(\sum_i (\alpha_i + mainx_i) sec), (\sum_i (\beta_i + mainy_i) sec)] \quad \forall sec \quad (39)$$

Placing distance constraints

The separation between equipment items i and j in both horizontal and vertical directions is determined using [Eqs. 40–42](#).

$$R_{i,j,sec} - Le_{i,j,sec} = x_{i,sec} - x_{j,sec} \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (40)$$

$$A_{i,j,sec} - B_{i,j,sec} = y_{i,sec} - y_{j,sec} \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (41)$$

$$U_{i,j,sec} - De_{i,j,sec} = H_{sec} \sum_k k (V_{i,sec,k} - V_{j,sec,k}) \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (42)$$

To guarantee that none of these intermediate distance expressions can assume negative values, the additional inequalities in [Eqs. 43–48](#) are introduced.

$$R_{i,j,sec} \leq M_{sec} W x_{i,j} \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (43)$$

$$Le_{i,j,sec} \leq M_{sec} (1 - W x_{i,j}) \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (44)$$

$$A_{i,j,sec} \leq M_{sec} W y_{i,j} \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (45)$$

$$B_{i,j,sec} \leq M_{sec} (1 - W y_{i,j}) \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (47)$$

$$De_{i,j,sec} \leq M_{sec} (1 - W z_{i,j}) \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (48)$$

Consequently, the overall rectilinear (Manhattan) distance separating items i and j is expressed through [Eqs. 49–50](#).

$$TD_{i,j,sec} = R_{i,j,sec} + Le_{i,j,sec} + A_{i,j,sec} + B_{i,j,sec} + U_{i,j,sec} + De_{i,j,sec} \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (49)$$

$$TD_{i,j,sec} = TD_{j,i,sec} \quad \forall i, j, sec : i \neq j, group_{i,sec} = 1, group_{j,sec} = 1 \quad (50)$$

Safety distance constraints

Safety separation requirements are based on the equipment cost values from Model 1 as inputs. These constraints, originally formulated and justified in [27], are implemented via Eqs. 51-53 to ascertain whether equipment item j falls within the explosion hazard radius of equipment item IP . The rectilinear distance between IP and j is subsequently computed by Eq. 54. The area of exposure associated with item IP and its corresponding base Maximum Probable Property Damage (MPPD) value are calculated according to Eqs. 55 and 56, respectively.

$$\begin{aligned} Din_{IP,j,sec} &\leq Dei_{IP} Y_{IP,j} \quad \forall IP, j, sec : IP \neq j, group_{IP,sec} \\ &= 1, group_{j,sec} = 1 \end{aligned} \quad (51)$$

$$\begin{aligned} Dout_{IP,j,sec} &\geq Dei_{IP} (1 - Y_{IP,j}) \quad \forall IP, j, sec : IP \neq j, group_{IP,sec} \\ &= 1, group_{j,sec} = 1 \end{aligned} \quad (52)$$

$$\begin{aligned} Dout_{IP,j,sec} &\leq Mm (1 - Y_{IP,j}) \quad \forall IP, j, sec : IP \neq j, group_{IP,sec} \\ &= 1, group_{j,sec} = 1 \end{aligned} \quad (53)$$

$$\begin{aligned} TD_{IP,j,sec} &= Din_{IP,j,sec} + Dout_{IP,j,sec} \quad \forall IP, j, sec : IP \neq j, group_{IP,sec} \\ &= 1, group_{j,sec} = 1 \end{aligned} \quad (54)$$

$$\begin{aligned} Ve_{IP} &= CP_{IP} + \left[\sum_j CP_j Y_{IP,j} - \left(\frac{CP_j \cdot Din_{IP,j,sec}}{Dei_{IP}} \right) \right] \quad \forall IP, sec \\ &: group_{IP,sec} = 1, IP \neq j, group_{j,sec} = \end{aligned} \quad (55)$$

$$ohmz_{IP} = Df_{IP} Ve_{IP} \quad \forall IP, sec : group_{IP,sec} = 1 \quad (56)$$

The final, adjusted MPPD cost is then derived using Eq. 57. Here, the binary variable $Zik_{IP,ki}$ selects the most suitable protection device configuration for equipment item IP .

$$\begin{aligned} ohm_{IP} &= \sum_{Ki} grammar_{IP,Ki} ohmz_{IP} Zik_{IP,ki} \quad \forall IP, sec : group_{IP,sec} \\ &= 1 \end{aligned} \quad (57)$$

Precisely one protection configuration must be assigned to each equipment item IP , as stipulated by Eq. 58.

$$\sum_{Ki} Zik_{IP,ki} = 1 \quad \forall IP, sec : group_{IP,sec} = 1 \quad (58)$$

Layout design boundary constraints

The x- and y-coordinates of each equipment item are defined with respect to the geometric center of its footprint, inclusive of the supplementary maintenance clearance zones, per Eqs. 59 and 60.

$$x_{i,sec} \geq 0.5l_i + vmainx_i \quad \forall i, sec : group_{i,sec} \quad (59)$$

$$y_{i,sec} \geq 0.5d_i + vmainy_i \quad \forall i, sec : group_{i,sec} \quad (60)$$

To ensure that no equipment item is positioned beyond the designated plant footprint, the following boundary restrictions are imposed:

$$x_{i,sec} + 0.5l_i + vmainx_i \leq Xmax_{sec} \quad \forall i, sec : group_{i,sec} \quad (61)$$

$$y_{i,sec} + 0.5d_i + vmainy_i \leq Ymax_{sec} \quad \forall i, sec : group_{i,sec} \quad (62)$$

Notably, when **Eqs. 59-62** are applied simultaneously across the seven sections of the EFB biodiesel facility; the section boundaries tend to overlap significantly, as all lower bounds default to (0,0), resulting in the issue visualized in **Figure 3**. This overlap arises because every section's coordinate system originates at the origin. The conflict is resolved in Model 3, which reallocates the seven process sections as wholes rather than handling the 57 individual equipment items separately.

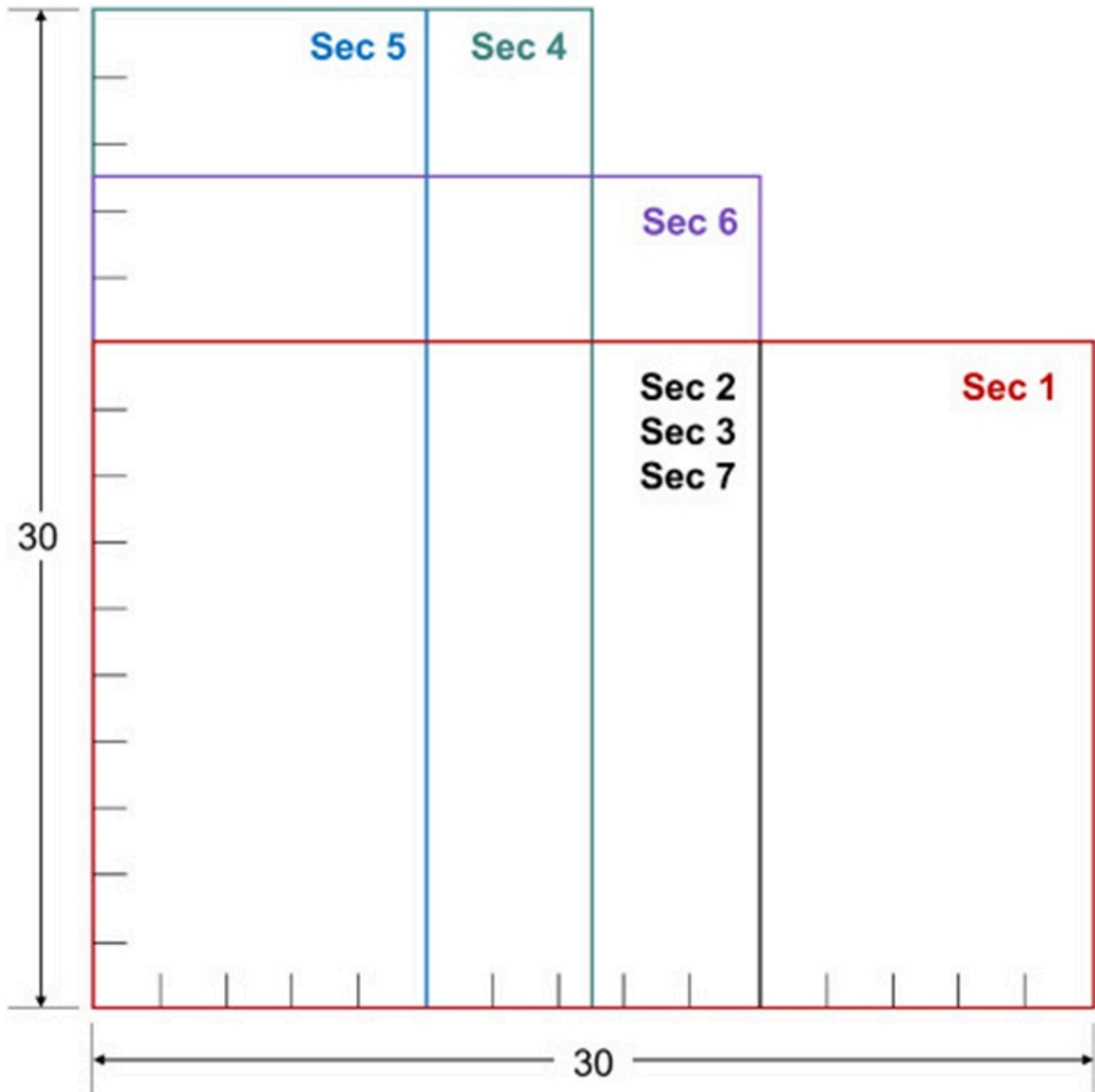


Figure 3. Illustration of boundary overlap when all section origins are fixed at (0,0), highlighting the necessity of Model 3 (schematic representation).

Area constraints

The total footprint required for the plant is computed using Eq. 63, where the binary variable $QS_{s,sec}$ selects one of S predefined rectangular area options, each characterized by dimensions AR_s , $Xbars$, and $Ybars$.

$$FA_{sec} = \sum_s AR_s QS_{s,sec} \quad \forall sec \quad (63)$$

$$\sum_s QS_{s,sec} = 1 \quad \forall sec \quad (64)$$

$$FA_{sec}NF_{sec} \geq guess_{sec} \quad \forall sec \quad (65)$$

$$Xmax_{sec} = \sum_s Xbar_s QS_{s,sec} \quad \forall sec \quad (66)$$

$$Ymax_{sec} = \sum_s Ybar_s QS_{s,sec} \quad \forall sec \quad (67)$$

$$NQ_{s,sec} \leq KnQS_{s,sec} \quad \forall sec \quad (68)$$

$$NF_{sec} = \sum_s NQ_{s,sec} \quad \forall sec \quad (69)$$

Additionally, the occupied area allocated to any given section must exceed the minimum land requirement determined from the outcomes of Model 1. This condition is enforced by [Eq. 70](#).

$$FA_{sec}NF_{sec} \geq guess_{sec} \quad \forall sec \quad (70)$$

Objective function for model 2: multi-floor layout

The objective of Model 2 is to minimize the aggregate cost associated with the multi-floor arrangement within each section. This includes inter-equipment piping expenses, pumping costs differentiated by horizontal and vertical components, land acquisition cost based on area, fixed floor construction charges, area-proportional floor construction charges, the realized Maximum Probable Property Damage (MPPD) cost, and expenditures on protection devices:

$$\begin{aligned} & Qs \\ & = \left[\sum_{i,j,sec:i \neq j, f_{i,j}=1, group_{i,sec}, group_{j,sec}=1} \left(\frac{C_{i,j}TD_{i,j,sec}}{0.3048} + C_{v,i,j}De_{i,j,sec} + Ch_{i,j}(R_{i,j,sec} + Le_{i,j,sec} + A_{i,j,sec} + B_{i,j,sec}) \right) + FC1 \right. \\ & \quad \sum_{sec} NF_{sec} + FC2 \sum_{s,sec} AR_s NQ_{s,sec} + LC \sum_{sec} FA_{sec} + 10^5 \\ & \quad \left. \sum_{IP,sec:group_{IP,sec}=1} ohm_{IP} + \sum_{IP,Ki,sec:group_{IP,sec}=1} Pik_{IP,Ki} Zik_{IP,Ki} \right] 10^{-5} \end{aligned} \quad (71)$$

Where $C_{i,j}$ represents the piping cost between equipment items i and j , $C_{v,i,j}$ and $Ch_{i,j}$ denote the vertical and horizontal pumping costs, respectively, and $FC1$ and $FC2$ indicate the fixed and area-dependent components of floor construction cost.

The formulation constitutes a Mixed-Integer Nonlinear Programming (MINLP) problem that minimizes the objective function defined in [Eq. 71](#), subject to the constraints listed in [Eqs. 25-70](#). The land unit cost is held constant at 676 \$/m² [\[23\]](#).

Model 3 — plant-wide section integration (Seven-section layout)

Model 3 constitutes the final optimization stage depicted in [Figure 2](#), focusing on the overall spatial arrangement of the seven process sections. To ensure consistency, the dimensions of each section in this stage are automatically aligned with the floor-area extents obtained from Model 2, as shown in [Eqs. 72 and 73](#).

$$alphag_{sec} = Xmax_{sec} \quad \forall sec \quad (72)$$

$$betag_{sec} = Ymax_{sec} \quad \forall sec \quad (73)$$

Intersection pumping costs in Model 3 are restricted to horizontal contributions only, since multi-floor effects are not considered at this level. Intersection piping costs are likewise included. These relationships are expressed in [Eqs. 74 and 75](#).

$$\begin{aligned} hcsec_{sec,secx} &= \sum_{i,j} Ch_{i,j} \quad \forall sec, secx : group_{i,sec}, group_{j,sec} = 1, f_{i,j} \\ &= 0, i \neq j, sec \neq secx \end{aligned} \quad (74)$$

$$\begin{aligned} csec_{sec,secx} &= \sum_{i,j} Cc_{i,j} \quad \forall sec, secx : group_{i,sec}, group_{j,sec} = 1, f_{i,j} \\ &= 0, i \neq j, sec \neq secx \end{aligned} \quad (75)$$

Note that the connectivity parameter $f_{i,j}$ equals zero whenever equipment item i in section sec connects to item j in section $secx$ across section boundaries ($f_{i,j} = 0$ for cross-section connections; otherwise, nonzero).

Dimension constraints ([Eqs. 76 and 77](#))

$$ll_{sec} = alphag_{sec}OO_{sec} + betag_{sec}(1 - OO_{sec}) \quad \forall sec \quad (76)$$

$$dd_{sec} = alphag_{sec} + betag_{sec} - ll_{sec} \quad \forall sec \quad (77)$$

Non-overlapping constraints for seven sections ([Eqs. 78–81](#))

$$\begin{aligned} xxx_{sec} - xxx_{secx} + ss(Eaa_{sec,secx} + Ebb_{sec,secx}) &\geq 0.8(ll_{sec} + ll_{secx}) \\ \forall sec, secx : sec \neq secx \end{aligned} \quad (78)$$

$$\begin{aligned} xxx_{sec} - xxx_{secx} + ss(1 - Eaa_{sec,secx} + Ebb_{sec,secx}) &\geq 0.8(ll_{sec} + ll_{secx}) \\ \forall sec, secx : sec \neq secx \end{aligned} \quad (79)$$

$$yyy_{sec} - yyy_{secx} + ss(1 + Eaa_{sec,secx} - Ebb_{sec,secx}) \geq 0.8(dd_{sec} + dd_{secx}) \quad (80)$$

$$\forall sec, secx : sec \neq secx$$

$$yyy_{sec} - yyy_{secx} + ss(2 - Eaa_{sec,secx} - Ebb_{sec,secx}) \geq 0.8(dd_{sec} + dd_{secx}) \quad (81)$$

$$\forall sec, secx : sec \neq secx$$

Connection distance constraints for seven sections (Eqs. 82–88)

$$RR_{sec,secx} - Lee_{sec,secx} = xxx_{sec} - xxx_{secx} \quad \forall sec, secx : sec \neq secx \quad (82)$$

$$AA_{sec,secx} - BB_{sec,secx} = yyy_{sec} - yyy_{secx} \quad \forall sec, secx : sec \neq secx \quad (83)$$

$$TDD_{sec,secx} = RR_{sec,secx} + Lee_{sec,secx} + AA_{sec,secx} + BB_{sec,secx} \quad \forall sec, secx : sec \neq secx \quad (84)$$

$$RR_{sec,secx} \leq ssWxx_{sec,secx} \quad \forall sec, secx : sec \neq secx \quad (85)$$

$$Lee_{sec,secx} \leq ss(1 - Wxx_{sec,secx}) \quad \forall sec, secx : sec \neq secx \quad (86)$$

$$AA_{sec,secx} \leq ssWyy_{sec,secx} \quad \forall sec, secx : sec \neq secx \quad (87)$$

$$BB_{sec,secx} \leq ss(1 - Wyy_{sec,secx}) \quad \forall sec, secx : sec \neq secx \quad (88)$$

Coordinate constraints for seven sections (Eqs. 89–93)

$$xxx_{sec} \geq 0.5ll_{sec} \quad \forall sec \quad (89)$$

$$yyy_{sec} \geq 0.5dd_{sec} \quad \forall sec \quad (90)$$

$$xxx_{sec} + 0.5ll_{sec} \leq xxx_{max} \quad \forall sec \quad (91)$$

$$yyy_{sec} + 0.5dd_{sec} \leq yyy_{max} \quad \forall sec \quad (92)$$

Total area constraint

$$FAs = xxx_{max}.yyy_{max} \quad (93)$$

Objective function for model 3: section integration

The objective for Model 3 is to minimize the combined costs associated with the seven-section layout, including inter-section piping, horizontal pumping, land area, and construction-related expenditures.

$$QQ = \sum_{sec, secx} [TDD_{sec, secx} (csec_{sec, secx} + hcsec_{sec, secx})] + (LC + FC1) FAs \quad (94)$$

This constitutes a Mixed-Integer Nonlinear Programming (MINLP) problem that minimizes the objective function given by [Eq. 94](#), subject to the constraints in [Eqs. 76-93](#).

Final equipment location for each section

Once the seven sections have been positioned, the coordinates and orientation of individual equipment items within each section must be adjusted to conform to the section-level placement and orientation determined by Model 3. The procedure for deriving these final equipment locations is described through the following equations.

First, the section with the lowest x- and y-coordinate values is identified as the reference origin using [Eqs. 95 and 96](#).

$$miniX = minimum_{sec} (xxx_{sec}) \quad (95)$$

$$miniY = minimum_{sec} (yyy_{sec}) \quad (96)$$

The effective dimensions of each equipment item are then updated according to the orientation of its assigned section (OOsec), as specified in [Eqs. 97 and 98](#).

$$newL_{i, sec} = l_i OO_{sec} + d_i (1 - OO_{sec}) \quad \forall i, sec : group_{i, sec} = 1 \quad (97)$$

$$newD_{i, sec} = l_i + d_i - newL_{i, sec} \quad \forall i, sec : group_{i, sec} = 1 \quad (98)$$

The adjusted coordinates for each section are computed via [Eqs. 99–101](#).

$$newX_{i, sec} = OO_{sec} (x_{i, sec} - 0.5Xmax_{sec} + xxx_{sec}) + (1 - OO_{sec}) [xxx_{sec} + (y_{i, sec} - 0.5Ymax_{sec})] \quad \forall i, sec : group_{i, sec} = 1, xxx_{sec} > miniX \quad (99)$$

$$newX_{i, sec} = x_{i, sec} OO_{sec} + y_{i, sec} (1 - OO_{sec}) \quad \forall i, sec : group_{i, sec} = 1, xxx_{sec} = miniX \quad (100)$$

$$\begin{aligned} newY_{i,sec} &= OO_{sec} [(y_{i,sec} - 0.5Y_{max_{sec}}) + yyy_{sec}] \\ &+ [(1 - OO_{sec}) (yyy_{sec} - x_{i,sec} - 0.5X_{max_{sec}})] \quad \forall i, sec : group_{i,sec} \\ &= 1, yyy_{sec} \geq miniY \end{aligned} \quad (101)$$

Observe that the updated equipment position is derived from the offset between the original equipment coordinates ($x_{i,sec}$ or $y_{i,sec}$) and the section centroid ($0.5X_{max_{sec}}$ or $0.5Y_{max_{sec}}$), for example, $x_{i,sec} - 0.5X_{max_{sec}}$ or $y_{i,sec} - 0.5Y_{max_{sec}}$. The section orientation OO_{sec} determines which adjustment term is activated: when $OO_{sec} = 1$ in Eq. 99, the expression $(x_{i,sec} - 0.5X_{max_{sec}} + xxx_{sec})$ applies; conversely, when $OO_{sec} = 0$, the term $[xxx_{sec} + (y_{i,sec} - 0.5Y_{max_{sec}})]$ is used. The logic for Eq. 101 mirrors that of Eq. 99.

Importantly, Eqs. 99 and 100 cannot be active simultaneously, as only one condition ($xxx_{sec} > miniX$ or $xxx_{sec} = miniX$) can hold. Figure 4 provides a schematic illustration of how section orientation is translated into the final equipment coordinates using Eqs. 95–101.

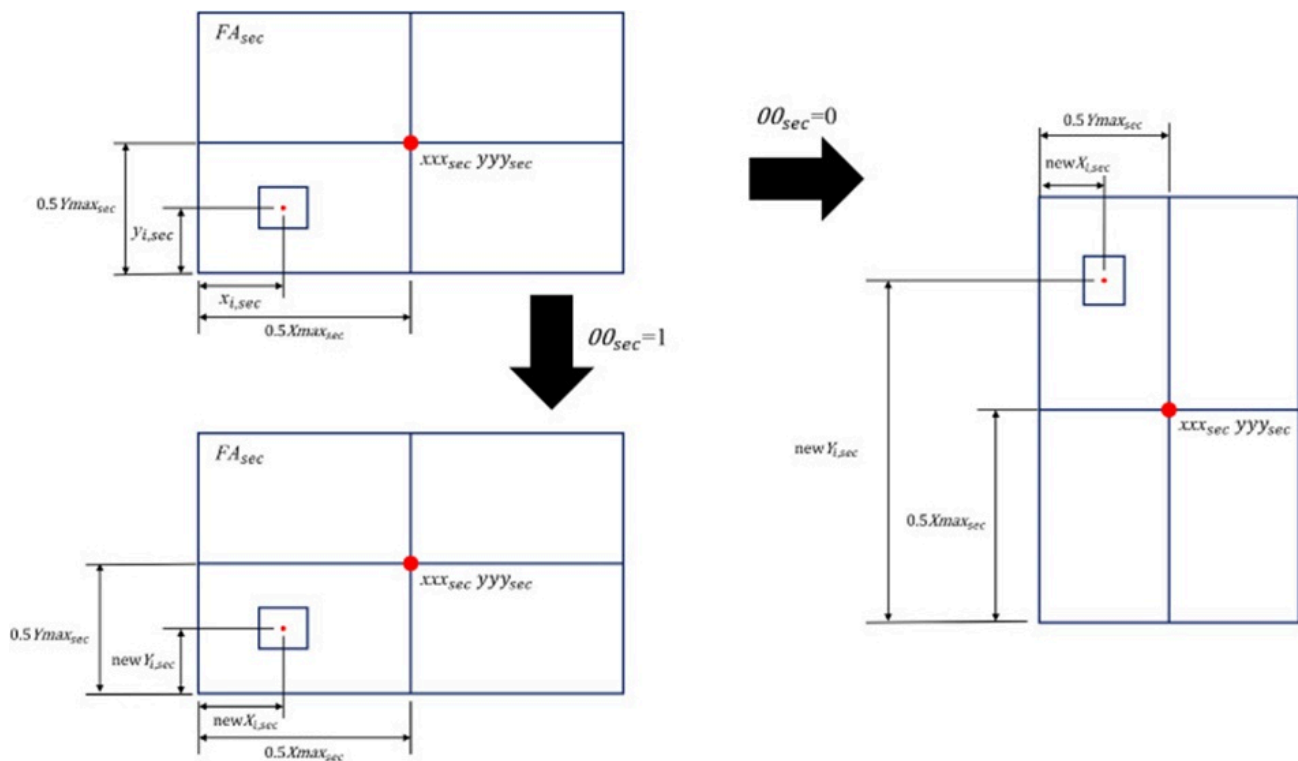


Figure 4. Schematic showing the transformation from section orientation to final equipment positioning.

Results and Discussion

The three-stage optimization approach is implemented on the empty fruit bunch (EFB) biodiesel process to determine an optimized plant layout. Key findings from each of the three models are presented and analyzed in the following subsections.

Outcomes of model 1: materials and structure

Model 1 was solved to minimize the combined cost of equipment and structural support, as defined by the objective in Eq. 22, while adhering to single-material-per-item rules (Eq. 1), mass balance equations for equipment and sections (Eqs. 2

and 3), and structural type assignment constraints (Eqs. 4 and 5). Input data included equipment footprint dimensions from Table 3, and material-specific cost adjustment factors from Table 2 [26]. These parameters were fed into the standard cost estimation correlations to ensure that material selections directly and consistently influence installed costs within the optimization.

Table 3. Rectangular equipment envelope dimensions applied for layout purposes (allowing 90° rotation).

Unit	No	alpha (m)	beta (m)	height (m)	Unit	No	alpha (m)	beta (m)	height (m)
Centrifugal gas compressor	1	1.09	0.43	0.6	Heat exchanger	30	2.1	2.1	1.05
Heater	2	1.1	3.8	1.1	Heat exchanger	31	2.1	2.1	1.05
Atmos tray dryer	3	5.17	4.19	4.29	Heat exchanger	32	2.1	2.1	1.05
Mixer	4	1.4	1.4	1.7	Pump	33	0.78	1	0.78
Gyratory crusher	5	2.17	5.56	2.1	Compressor	34	0.6	1.1	0.6
Rectangle screen	6	2	2	3	Mixer	35	1.4	1.4	1.7
Heater	7	0.78	2.15	0.6	Cooler	36	2.4	5.8	2.4
Agitated reactor	8	0.8	0.8	5	Agitated reactor	37	0.6	0.6	2
Mixer	9	1.4	1.4	1.7	Heat exchanger	38	2.1	2.1	2.1
Agitated reactor	10	0.8	5	0.8	Heat exchanger	39	2.1	2.1	2.1
Agitated reactor	11	0.8	5	0.8	Vertical vessel	40	0.5	0.5	3.7
Centrifugal gas compressor	12	1.1	0.43	0.6	Vertical vessel	41	0.3	1.3	1.8
Compressor	13	1.1	0.43	0.6	Decanter	42	0.6	3.7	0.6
Agitated reactor	14	1	1.15	1.35	Mixer	43	2.6	2.6	4.3
Agitated reactor	15	1	1.15	1.35	Cooler	44	2.3	5.8	2.3
Cyclone	16	1.38	1.38	2.07	Distillation column	45	0.8	0.8	9.14
Mixer	17	1.4	1.4	1.7	Distillation column	46	2.05	2.05	8.54
Heater	18	0.6	0.7	0.6	Pump	47	0.5	0.8	0.5
Heater	19	0.6	0.7	0.6	Mixer	48	2.6	2.6	4.3
Compressor	20	1.1	0.43	0.6	Compressor	49	0.6	1.1	0.6
Mixer	21	2.6	2.6	4.3	Heater	50	0.28	1.58	0.28
Cyclone dust coil	22	2	2	4	Mixer	51	1.4	1.4	1.7
Vertical vessel	23	1.2	1.2	3.7	Mixer	52	1.4	1.4	1.7
Vertical vessel	24	1.5	1.5	4.5	Heat exchanger	53	0.28	1.58	0.28

Cooler	25	2.4	5.8	2.4	Agitated reactor	54	1.5	1.5	12
Pump	26	0.5	0.5	0.8	Cooler	55	2.3	5.8	2.3
Mixer	27	1.4	1.4	1.7	Vertical vessel	56	0.45	0.45	3.66
Mixer	28	1.4	1.4	1.7	Mixer	57	1.4	1.4	1.7
Mixer	29	1.4	1.4	1.7					

The resulting optimization problem contained 377 constraints, 420 binary variables, and 1,007 continuous variables, producing an optimal objective value of 2,460.003 M\$. Carbon steel emerges as the preferred material for most applications, particularly in screening and cyclone operations, while nickel is entirely avoided ($zz3 = 0$ for all items). Stainless steel 304 is selected for the tray dryer and gyratory crusher.

The prevalence of carbon steel stems from its comparatively low material cost multipliers in [Table 2](#) compared with more corrosion-resistant alloys such as nickel. When applied to the base-cost equations, elevated multipliers substantially increase installed costs—especially for large or heavy units whose dimensions ([Table 3](#)) strongly drive the cost function.

Regarding structural design, the optimizer uniformly selects the higher-capacity option st2 (wd2, 1,500 kg/m²) for all seven sections, as determined by the binary choices in [Eqs. 4 and 5](#). This preference for greater load-bearing capacity per unit area reduces the upper mass bound in [Eq. 3](#). It facilitates compliance with minimum footprint requirements (later imposed in Model 2 via [Eq. 70](#)), ultimately yielding superior overall economics. Although the unit cost of the stronger structural type is higher, the integrated solution under [Eq. 22](#) favors it because it prevents unnecessary footprint expansion and generates downstream reductions in piping and pumping expenses realized in subsequent models—aligning with the overarching cost–safety co-optimization goal of the decomposition strategy.

Outcomes of model 2: multi-floor layout with safety devices

Model 2 simultaneously optimizes intra-section equipment placement, floor assignments, and protection device selections under the comprehensive cost objective in [Eq. 71](#), which encompasses piping, horizontal and vertical pumping, land area, fixed and area-proportional floor construction, realized MPPD costs, and protection device expenditures. Required inputs and constraints are sourced from equipment dimensions, maintenance clearance allowances, connectivity and pumping cost data, and Dow’s F&EI-derived exposure areas, base MPPD values, and device credit options.

To remain within GAMS academic license restrictions, the model is solved individually for each process section, as summarized in [Table 4](#). This sectional approach maintains full fidelity with respect to safety distances and constructability restrictions ([Eqs. 25–70](#)) while ensuring computational tractability.

Table 4. Computational characteristics and objective values for the three models (constraints, variables, CPU time).

Model	sec	Number of constraints	Number of discrete variables	Number of continuous variables	CPU time (min)	Objective value (M\$)
First objective	–	377	420	1007	2.51	2,460.003
Second objective	1	910	286	598	2.09	0.794
	2	540	176	390	2.35	3.129
	3	1,302	400	885	2.61	4.958
	4	1,640	496	1103	3.39	10.174

	5	1,982	601	1323	2.87	3.097
	6	1,366	423	942	2.34	28.978
	7	2,030	612	1355	2.87	31.127
Third objective	—	506	172	414	1.94	6.642

Safety considerations and economic performance are tightly coupled. For every hazardous unit designated as IP, the optimizer selects the protection device configuration that delivers the lowest loss-control credit factor (k_6), thereby minimizing the actual probable property damage cost (ohmIP) relative to the unprotected baseline (ohmzIP) while keeping the incremental device cost competitive at the section level (Table 5). This outcome reflects the inherent trade-off between upfront protection expenditure and the monetized reduction in accident-related exposure, as enforced by Dow's F&EI-based separation distances and area-of-exposure constraints.

Table 5. Chosen protection device configurations for key hazardous units (IP) and corresponding MPPD reductions (based on Dow's F&EI).

sec	IP	VelP(\$/10 ⁵)	ohmzIP (\$/10 ⁵)	Zik1	Zik2	Zik3	Zik4	Zik5	Zik6	ohmIP (\$/10 ⁵)
2	8	106.812	64.087						1	7.498
	10	94.768	66.337						1	7.762
	11	94.768	66.337						1	7.762
3	14	264.304	166.511						1	19.482
	15	264.061	166.358						1	19.464
4	23	102.014	71.41						1	33.206
	24	160.441	112.309						1	52.224
5	37	318.544	222.981						1	26.089
6	40	35.396	23.007						1	10.698
	41	372.805	246.051						1	114.414
	45	118.636	51.014						1	23.721
	46	667.273	280.255						1	130.318
7	54	5,471.35	2,516.821						1	294.468
	56	33.138	20.546						1	9.554

Note: Values are presented in solver-scaled units: \$/10⁵ (= 0.1 MUSD). Multiply by 0.1 to convert to M\$.

Three primary mechanisms explain the observed multi-floor configurations. First, vertical stacking serves as an efficient strategy for meeting Dow's F&EI separation requirements in space-constrained areas, thereby limiting footprint expansion and reducing overlap of hazard zones. Second, elevation incurs a hydraulic penalty—the model explicitly accounts for vertical pumping costs, while horizontal pumping is approximated at 10 % of vertical—so inter-floor routing is restricted to cases where shorter piping runs or enhanced safety separations provide sufficient benefit. Third, practical constructability is maintained by requiring the heaviest equipment item in each section to be placed on the ground floor (Eq. 25), thereby

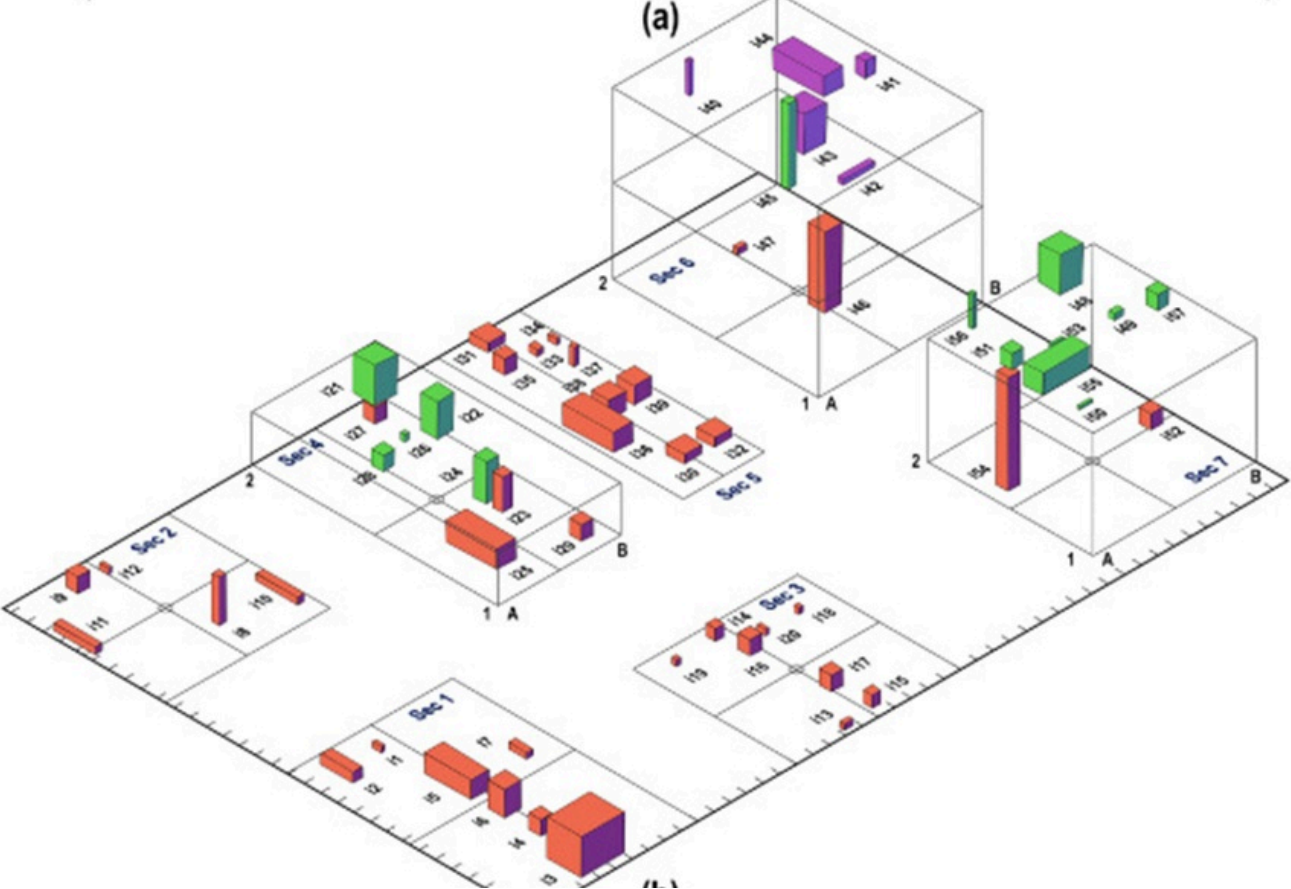
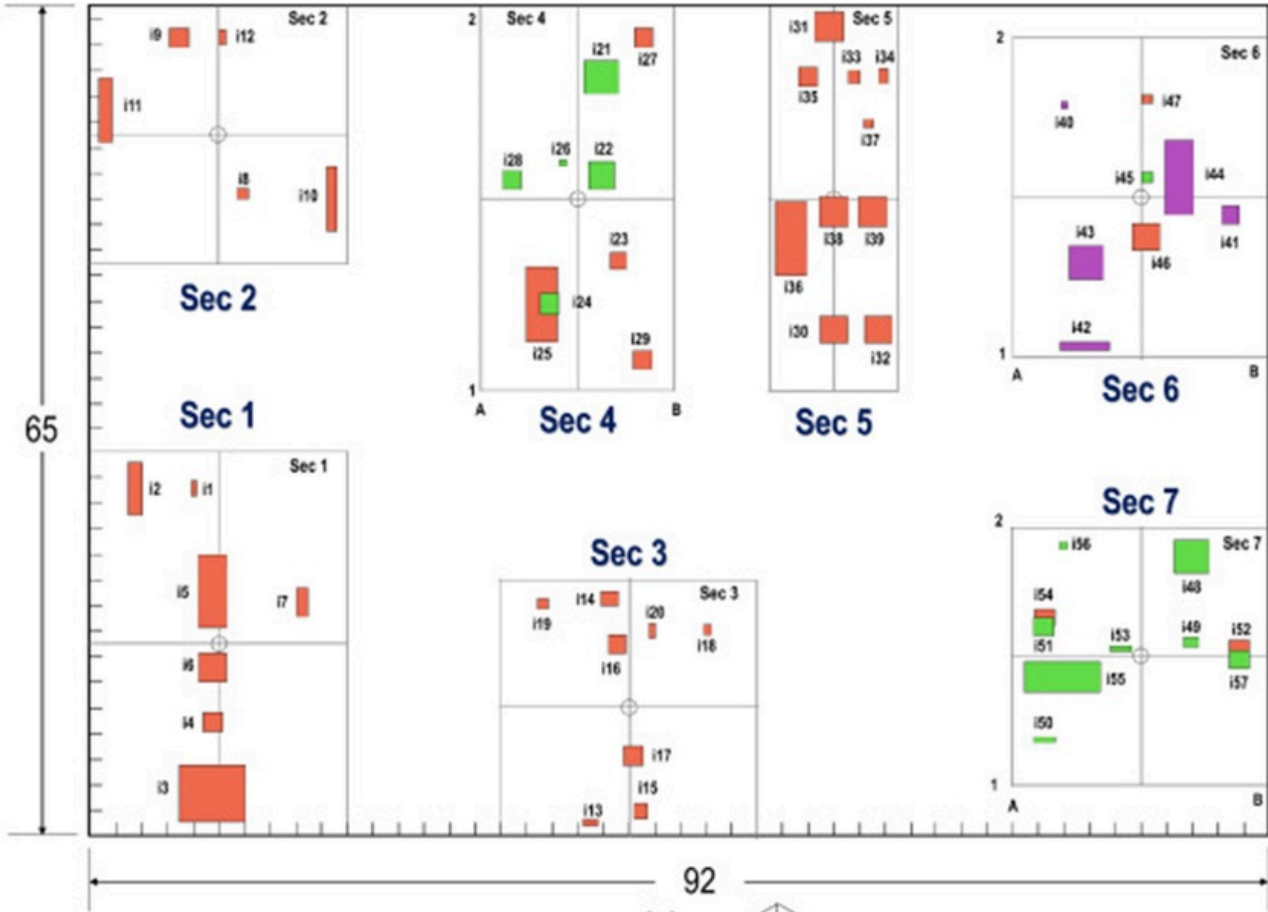
lowering overall civil structural loading, reducing pumping head demands, and supporting standard maintenance accessibility guidelines.

Outcomes of model 3: seven-section integration

Model 3 determines the optimal placement and orientation of the seven rectangular section footprints produced by Model 2, optimizing their central coordinates and rotational alignment under strict non-overlap conditions and rectilinear interconnection requirements. The resulting compact overall site occupies a 92 × 65 m rectangle (total area 5,980 m²), as detailed in **Table 6** and depicted in **Figures 5a** (top-down plan) and **5b** (three-dimensional isometric view). A high-fidelity 3D rendering generated in AutoCAD Plant 3D is shown in **Figure 6**. To shorten connection lengths, the solver assigns orientation flags (ooscc) that align section boundaries with the dominant process flow direction.

Table 6. Model 3 section integration results: section centroid coordinates, orientation indicators, dimensions, and overall plant footprint area.

sec	xxx	yyy	oo	ll	dd	xxxmax	yyymax	FAs
1	10	15		20	30	92	65	5980
2	10	55		20	20			
3	42	10		20	20			
4	38	50	1	15	30			
5	58	50	1	10	30			
6	82	50	1	20	25			
7	82	14		20	20			



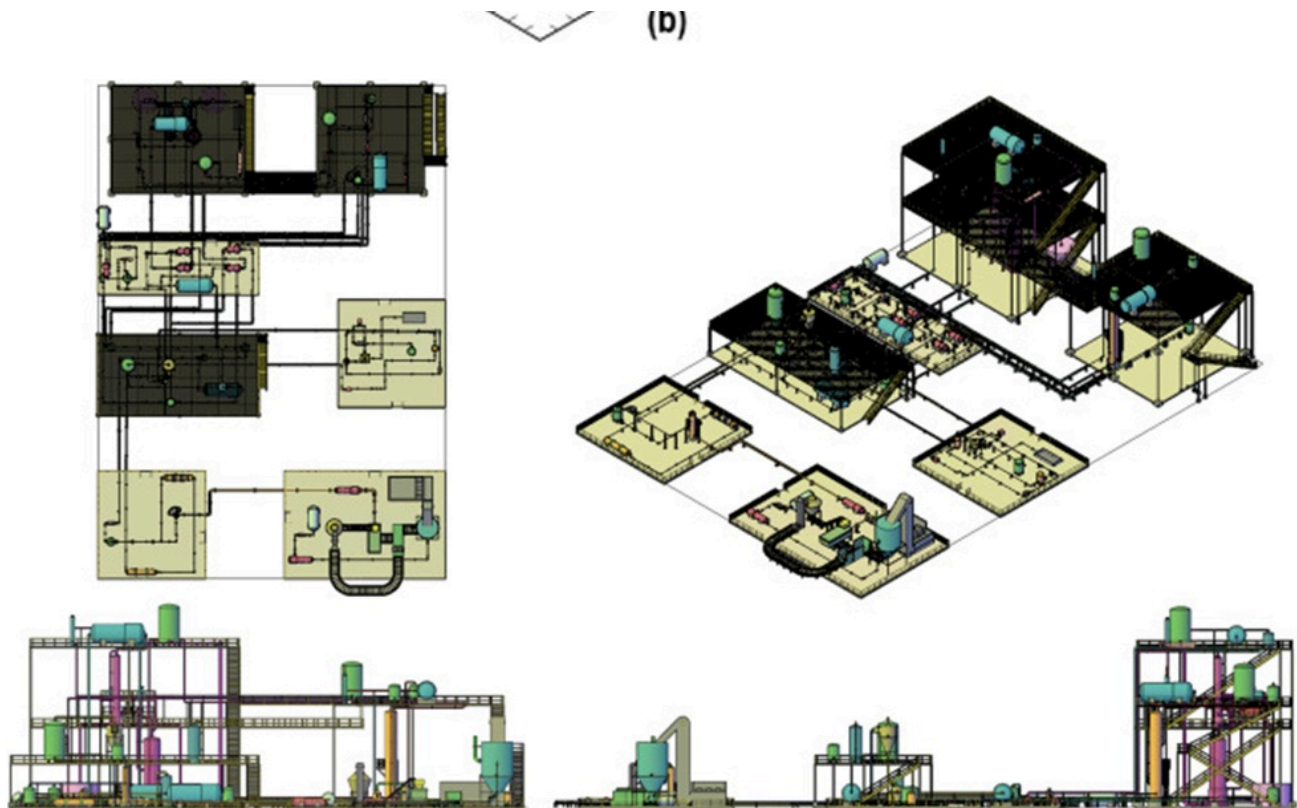


Figure 6. High-resolution plant layout visualization produced in AutoCAD Plant 3D.

The arrangement adheres to economic logic. Inter-section separations Eqs. 82–88 are minimized in accordance with connection expenses and pumping demands as defined in the objective (Eq. 94). As a result, sections with extensive mutual connectivity are positioned in proximity. At the same time, those with limited linkages are placed toward the periphery. This clustering strategy reduces piping costs and preserves interior space for future growth.

All safety and operational stipulations inherited from Model 2 are preserved in Model 3. The input section rectangles already embed required maintenance clearances, hazard separation zones, and structural capacity limits. Consequently, the integrated plant layout upholds these conditions without needing supplementary overlap verification Eqs. 76–81. Following section positioning, the coordinates of individual equipment items are transformed from local section reference frames to global plant coordinates using Eqs. 95–101. The final configuration exhibits logical process sequencing: high-capacity separation and fractionation units are situated adjacent to one another, thereby reducing both piping runs and associated pumping energy consumption.

Effect of structure- and land-cost parameters on layout

Sensitivity analyses were conducted by varying two key economic parameters: (i) raising the unit cost of structural type 2 (1,500 kg/m² capacity) from 300 to 450 \$/m², and (ii) halving the land unit cost from 676 to 338 \$/m². Structural cost influences Model 1 (material and structural selection; Eq. 22), whereas land cost affects the objectives in Models 2 and 3 (sectional and plant-wide layouts; Eqs. 71 and 94).

Effect of changing structure cost

Increasing the cost of the higher-capacity structural type 2 prompts the optimizer to assign all sections to the lower-capacity type 1 ($wd1 = 1$). This shift induces two main responses. First, minimum footprint requirements rise for several sections compared with the base-case solution. Second, certain heavy equipment items are reassigned to lighter materials (e.g., item i25 switches to titanium, $zz4 = 1$) to comply with the 1,000 kg/m² load limit imposed by type 1.

The underlying economic reasoning is clear. Although type 1 offers reduced load-bearing capability, its lower unit price offsets the modest increases in required area and the occasional need for costlier but lighter materials. Consequently, the objective value in Model 1 rises slightly. This occurs because the less expensive structural option leads to marginally larger section footprints in Model 1, which, in turn, influence piping and pumping trade-offs during Model 2 optimization.

Effect of changing land cost

Reducing the land unit cost by half lowers the objective values in Models 2 and 3 for all sections. This change elicits substantial modifications to the layouts. Prominent alterations include expanding Section 3 from 20×20 m to 20×25 m and redistributing equipment within Section 4—for example, item i21 is relocated to the ground floor, while others remain elevated.

At the plant-wide scale, the impact is especially pronounced. The overall site footprint transitions from a predominantly horizontal to a more vertically oriented configuration. This shift directly results from the diminished penalty associated with area expansion in the objectives of Eqs. 71 and 94. With land becoming more affordable, the optimizer prioritizes operational improvements—enlarging section footprints to shorten inter-section piping runs and provide more generous accommodation for safety exclusion zones. All safety-related constraints, including non-overlap rules and Dow's F&EI-derived hazard envelopes, continue to be fully satisfied despite the increased spatial extent.

Taken together, these sensitivity results highlight a fundamental economic trade-off: lower land costs favor expansive layouts that enhance process efficiency and safety compliance, whereas higher structural costs drive compact arrangements supported by lighter materials and reduced load-bearing demands to limit civil investment.

Model validation and comparative analysis

Baseline comparison

A traditional single-floor reference design was developed in accordance with industry guidelines: grid-arranged equipment placement using carbon steel for non-aggressive services, minimum code-required clearances, and standalone safety engineering. Relative to this benchmark (Table 7), the proposed three-stage MINLP methodology delivers a 28.9% decrease in total capital expenditure (from 115.82 M\$ to 82.30 M\$), a 51.97% reduction in land area requirement (from 12,450 m² to 5,980 m²), and an 18.8% drop in unprotected Maximum Probable Property Damage (MPPD) from 310.0 M\$ to 251.68 M\$ attributable solely to hazard-conscious spatial organization. When protection device configurations (k6 factors) are co-optimized with layout, the post-protection MPPD falls further to 29.45 M\$, corresponding to a 69.0% reduction relative to the 95.0 M\$ baseline. The dominant hazardous unit IP54 governs the facility-wide exposure computation (the highest ohmZIP value), and the protection performance indicators reported in Table 5 verify that simultaneous layout–safety optimization surpasses conventional sequential workflows, in which spatial planning and protective measures are addressed separately.

Table 7. Comparative performance metrics: conventional single-floor design versus optimized multi-floor configuration.

Performance metrics	Conventional design	Optimized design
Total capital cost (M\$)	115.82	82.30
Plant land envelope (m²)	12,450	5,980
Floor used (per section)	1 (all sections)	1–3 (varied)
MPPD before protection (M\$)	310.0	251.68
MPPD after protection (M\$)	95.0	29.45

Sensitivity analysis

The robustness of the optimization framework was evaluated by varying four key parameters (Table 8): land unit cost ($\pm 50\%$), structural load capacity (1,000–2,000 kg/m²), material cost index (+20% to +40%), and safety separation multiplier ($\pm 20\%$). The model exhibits reliable convergence under all tested conditions. Variations of $\pm 30\%$ in land costs prompt reallocation of floor assignments, with lower land prices favoring horizontal sprawl and higher land prices encouraging greater vertical utilization. Lowering structural capacity to 1,000 kg/m² requires substituting titanium for selected heavy equipment items, resulting in a 6.3% increase in capital cost. A 20% increase in mandated safety distances necessitates greater vertical separation to preserve the fixed 5,980 m² footprint, thereby confirming the value of the multi-floor approach. These behavioral shifts are consistent with the economic trade-offs encoded in Eq. 71 and the Dow F&EI-based spacing rules.

Table 8. Sensitivity results for principal design parameters (land cost, structural capacity, material cost index, safety-distance factor).

Parameter	Base value	Variation range	Total cost variation (%)	Structural/Operational response
Land cost (\$/m ²)	676	−50% to +50%	−6.8 to +7.9	Floor redistribution near $\pm 30\%$
Structure capacity (kg/m ²)	1,500	1,000 to 2,000	−1.4 to +6.3	Material substitution at 1,000
Material cost index	1.0	+20% to +40%	+3.8 to +8.2	Threshold at $\sim +35\%$ (alternative materials)
Safety distance factor	1.0	$\pm 20\%$	−2.8 to +3.9	Vertical expansion at +20%

Safety integration impact assessment

Three distinct cases were evaluated: (C1) optimization without any safety constraints, (C2) optimization under fixed regulatory separation distances with conventional relief systems, and (C3) full economic–risk co-optimization as implemented in the present model. As shown in Table 9, case C3 yields the lowest realized MPPD (1.47 M\$), accompanied by a moderate increase in capital expenditure relative to C2, while achieving the highest risk-mitigation ratio (8.44× relative to the unconstrained baseline). Over a 20-year Net Present Value (NPV) horizon that incorporates expected accident losses, both C2 and C3 outperform C1; however, C3 exhibits a marginally lower NPV than C2 due to greater initial investment in protective systems, which in turn provides markedly superior control over low-probability, high-consequence events—critical for regulatory approval and insurance considerations.

Table 9. Comparison of safety-integration approaches: unconstrained, fixed-spacing regulatory, and full cost–risk optimized designs.

Configuration	Initial CAPEX (M\$)	MPPD (M\$)	Risk-reduction factor	NPV (M\$)
C1: No safety constraints	71.2	12.4	1.00	−89.6
C2: Fixed regulatory distances	78.6	4.8	2.58	−83.4
C3: Integrated optimization	82.3	1.47	8.44	−83.8

- a) Relative to the unconstrained configuration.
- b) NPV calculated over 20 years at an 8% discount rate, inclusive of expected loss.

Computational performance vs metaheuristics

The proposed staged MINLP solution remains computationally tractable within academic licensing constraints. In contrast, a single monolithic formulation exceeds the allowable variable limits and fails to converge within realistic time constraints, as indicated in **Table 4**. **Table 10** illustrates that the decomposition strategy delivers better objective values, substantially shorter CPU times, and narrower optimality gaps than both the monolithic MINLP and alternative metaheuristic techniques.

Table 10. Computational efficiency comparison: proposed three-stage decomposition versus monolithic MINLP and metaheuristic methods.

Solution method	Variables	CPU time (min)	Objective (M\$)	Optimality gap (%)
Proposed decomposition				
Stage 1: Material selection	1,427	2.51	–	0.02
Stage 2: Multi-floor layout (7 sections)	566–1,967 ^a	18.52	–	0.03–0.09
Stage 3: Section integration	586	1.94	–	0.02
Total decomposed	–	22.97	82.30	< 0.1
Alternative methods				
Monolithic MINLP ^b	> 8,500	> 30 ^c	NE	–
Genetic algorithm	–	125.3	84.72	2.94 ^e
Simulated annealing	–	142.6	83.91	1.96 ^e

^a) Range across seven sections.

^b) Exceeds GAMS academic license; objective not evaluated (NE).

^c) Terminated at time limit without convergence.

^d) Heuristic methods (parameters: GA = 100 generations, SA = 5,000 iterations).

^e) Gap relative to decomposed solution.

The all-in-one model involves more than 8,500 variables, surpassing the GAMS Academic license caps of 2,500 variables and constraints. Execution under academic licensing is therefore infeasible, and a time-restricted trial run terminated without convergence after 30 minutes, underscoring the practical necessity of the hierarchical decomposition approach summarized in **Table 10**.

Process assumption and impact assessment

To verify the validity of the simplified hydraulic model used for pumping cost estimation, section-specific pressure drop values computed from detailed correlations were compared with the single-phase approximation used in the optimization. **Table 11** reveals discrepancies ranging from -8.0 % to +13.6 %, yet the overall effect on total pumping cost remains below 2 %, thereby supporting the reliability of the derived economic outcomes. Sections characterized by liquid–vapor or hydrogen-rich streams show the smallest deviations, whereas the pretreatment section, which processes solid-containing streams, exhibits the largest deviation at 13.6 %—still negligible from an economic perspective.

Table 11. Assessment of the accuracy of pressure-drop simplification across process sections.

Section	Phase	ΔP (rigorous) (kPa)	ΔP (simplified) (kPa)	Relative error (%)	Cost impact (%)
Pretreatment	Solid (EFB)	12.5 ± 0.8	14.2 ± 0.5	+13.6	+1.8
Pyrolysis	Mixed phase	28.3 ± 1.2	26.7 ± 0.9	−5.7	−0.7
Combustion	Gas-solid	18.7 ± 0.9	17.2 ± 0.6	−8.0	−1.1
Separation	Liquid-vapor	45.6 ± 1.5	43.8 ± 1.1	−3.9	−0.5
Hydrotreating	Liquid + H ₂	62.4 ± 2.1	59.1 ± 1.8	−5.3	−0.7
Weighted average	-	-	-	−2.8	−0.4

Conclusion

This study presents a Mixed-Integer Nonlinear Programming (MINLP) framework designed for multi-floor process plant layout optimization, integrating quantified safety considerations directly alongside economic objectives within a unified decision space and addressing the problem via a computationally efficient three-stage decomposition strategy. Compared with a standard single-floor, grid-oriented reference design, the resulting optimized configuration achieves simultaneous reductions in capital investment and land footprint while enhancing inherent safety performance. These improvements stem from three interrelated mechanisms: (i) vertical arrangement leverages elevation to reduce horizontal land use and minimize rectilinear interconnection lengths; (ii) exclusion zones derived from Dow's Fire and Explosion Index (F&EI) guide the placement of high-hazard units to limit escalation potential, while the model concurrently selects optimal passive protection measures; and (iii) mandatory ground-floor positioning of the heaviest equipment in each section controls elevation-induced head requirements and safeguards Net Positive Suction Head (NPSH) availability on suction lines, thereby preventing unanticipated hydraulic inefficiencies. The joint optimization of spatial layout and protective devices proves economically meaningful—fully integrated safety yields substantially greater reductions in monetized exposure compared with conventional fixed separation distances at similar investment levels. From a computational standpoint, the decomposed approach remains solvable using academic-grade resources. It produces solutions with narrow optimality gaps, in contrast to a single monolithic MINLP formulation that surpasses practical variable limits and fails to converge within acceptable time frames. Finally, validation of the simplified hydraulic assumptions demonstrates that pressure-drop approximations introduce only small deviations in pumping cost estimates, thereby reinforcing confidence in the economic outcomes. Collectively, the proposed methodology offers a systematic, transparent, and repeatable workflow—from Aspen Plus process stream data through to AutoCAD Plant 3D layout deliverables—suitable for real-world engineering implementation.

Limitations and challenges

- The full monolithic MINLP formulation exceeds GAMS academic license restrictions on variables and constraints; consequently, the three-stage decomposition was adopted to ensure solvability, although this may sacrifice some potential cross-stage global optimality.
- The heaviest equipment item in each section is fixed at ground level as an engineering heuristic. At the same time, this reduces the search space and aligns with practical constructability, but it limits the flexibility of vertical placement decisions.

- Safety assessment depends exclusively on Dow's F&EI index, utilizing predefined exposure radii and damage factors along with a finite set of enumerated protection options; the model does not incorporate scenario-driven Quantitative Risk Assessment (QRA).
- Protection is restricted to discrete device configurations with literature-derived credit factors and costs (k1–k6); continuous optimization of passive barrier placement or sizing (e.g., blast walls) is not included.
- Equipment items are modeled as rectangles permitting only 0° or 90° rotations under a rectilinear (Manhattan) distance metric, and available section footprints are limited to seven pre-specified rectangular candidates (S1–S7); site-specific obstacles, pipe rack corridors, and emergency egress pathways are excluded.
- Material selection is confined to a discrete set with associated cost adjustment factors; explicit modeling of corrosion allowances or service-specific degradation mechanisms is omitted.
- Structural unit costs are based on vendor quotations, while land costs adopt a fixed baseline value (676 \$/m²) that may not reflect regional or market-specific variations.
- The “conventional design” reference case represents an internal approximation rather than an existing industrial facility. However, plant-wide results were cross-verified using Aspen Plus simulations and AutoCAD visualizations; no physical pilot implementation was conducted.

Future work

- Integrate detailed pipe-network hydraulics, including line sizing, pump performance curves, variable-frequency drives, and explicit NPSH constraints; simultaneously optimize utility pipe rack routing and elevation profiles to reduce energy consumption and cavitation risks.
- Incorporate explicit constraints for aisle clearances, crane access envelopes, pipe rack corridors, fire roads, and evacuation pathways; extend equipment orientation to continuous angles to avoid site-specific obstacles.
- Link material selection to fluid chemistry, operating temperature, required corrosion allowances, and full life-cycle cost implications; introduce options for mixed-material construction and internal protective coatings as additional decision variables.
- Account for uncertainties in land pricing, structural costs, material indices, and safety parameters; advance beyond deterministic sensitivity to robust optimization or chance-constrained formulations that consider probabilistic distributions.
- Incorporate Life-Cycle Costing (LCC) and Life Cycle Assessment (LCA) elements, including energy and carbon pricing, flare/vent penalties, and insurance costs linked to MPPD estimates, to capture extended time-horizon economic and environmental impacts.
- Establish and maintain an open-access repository containing the GAMS model code, AutoCAD layout files, Aspen Plus simulation inputs, and plant walkthrough videos to facilitate external validation, replication, and application to additional feedstocks or process configurations.

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Conflict of interest

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