Design based Constraint Handling for Site Layout Planning

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Abstract

Site layout planning (SLP) constraints are handled heuristically or through a mathematical approach, as presented in the SLP literature. The real-life constraints of SLP are modelled as mathematical equations and are attempted to be handled through optimisation models. It is observed that the existing mathematical SLP models handle a limited number of constraints in comparison to what is handled by practitioners in practice. This study outlines a design-based workflow that enables SLP practitioners to handle SLP constraints and reduces the number of infeasible solutions to SLP problem. Firstly, the constraints of SLP are categorised to form constraints typology, and it is understood that the spatial constraints of SLP have facets that can be modelled and handled through design. A test case is developed to demonstrate the design-based handling of SLP constraints. The spatial constraint handling for SLP is presented through single regular-shaped temporary facility (TF) layout variations. The TF's variations enabled ascertaining the possibility of including TFs of different shapes and sizes. The results indicated a reduction in mathematical solution search space; consequently, the search for the optimal solutions for the SLP problem is expected in a timely manner. The implementation of the developed design-based constraint handling approach for SLP needs to be studied in conjunction with the mathematical models and remains an area for further study.

Keywords –

Site Layout Planning, Project Design, Building Information Modelling, Optimisation

1 Introduction

Construction site layout planning (SLP) encompasses organisation of construction project's physical elements in a safe and efficient manner. This includes positioning of temporary facilities (TFs), planning for roads and walkways for internal movement of site personnel, material shifting and equipment [1]. The SLP studies have tried but are not limited to minimise the material handling by finding optimal positions for the TFs [2]. These studies have focused on modelling the SLP problem as a mathematical problem and solving for an optimal solution to definitive objectives bounded by some constraints [3], whereas in practice there are many constraints handled by the SLP practitioners utilising heuristics while planning layouts [4].

Such incomprehensive problem representation results in sub-optimal layouts and limits the implementation of the SLP optimisation models. These optimisation models present a solution finding approach to the SLP, although the process involves decision-making based on objective and subjective goals. While the objective goals are presented as fitness function in the mathematical form of representation, the subjective goals of SLP are left for the planners to manage [5]. The mathematical representation of a real-life problem of SLP includes objective function(s) subjected to constraints to limit the space for solution search. The parameters like productivity, cost of project, safety on construction site, noise levels, security are mathematically modelled as objective functions to be optimised subjected to some real-life constraints depicted as mathematical bounds. These mathematical bounds restrict the infeasible solutions to become part of the feasible set [5].

Such restrictions mimic the actual solution search strategy adopted by the site layout planners while planning SLP using their experience. In practice the SLP practitioners handle the site constraints utilising the experience gained but considering the intertwined nature of construction projects the handling of multiple objectives subjected to various constraints surpasses the mental computability of humans [6]. Thus the mathematical representation of SLP problem is presented as a method to solve for SLP in the existing literature. These mathematical formulations present limited constraints handling in the optimisation model and thus the unattended practical constraints remain challenges for practitioners to address, resulting in limited adoption of mathematical approaches for SLP [4].

This study reviews the mathematical approaches to SLP, identifies the constraints handled in the SLP literature, develops a constraint typology, and presents a design-based approach to handle the constraints of SLP. The developed design-based strategy is targeted to handle the hard constraints of the SLP problem, consequently lowering the constraints to be handled either mathematically or heuristically.

2 Construction SLP problem and its Constraints

The SLP problem in the literature is represented as either continuous or discrete site space organisation problem targeted to mathematically find optimal positions for TFs. The mathematical models attempt to depict the SLP problem closer to reality, the formulation differs depending upon the geometrical representation considered in the research. Therefore based on geometrical representations presented in SLP studies the problem of SLP can be divided into two namely continuous, and discrete.

The site space is considered as continuous when the TFs can be positioned anywhere on the site.as shown in Figure 1. The centroid of the TFs is considered as decision variable to identify the position of the TFs on the available site area [7] in continuous SLP problem.

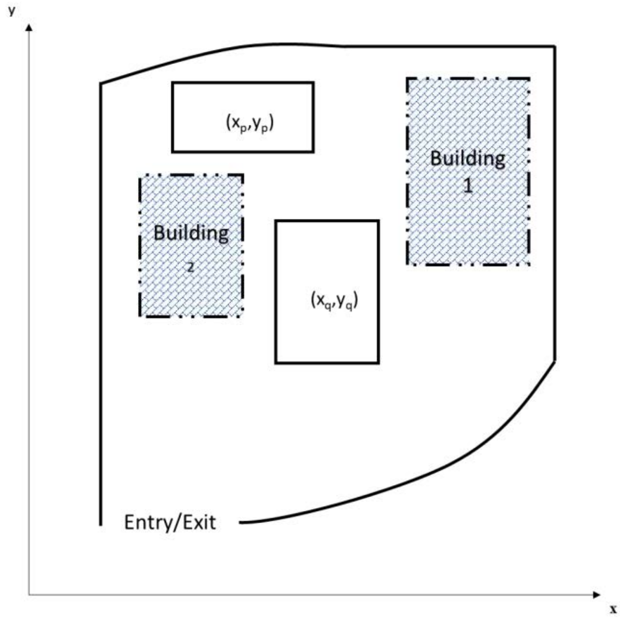

Figure 1. Continuous SLP problem representation.

On the contrary to continuous SLP, the locations to accommodate TFs are identified in prior and then the positioning of TFs is handled as part of the discrete SLP problem [8] as depicted in Figure 2. This formulation poses another challenge for the SLP practitioners of identifying the available locations on the site area for accommodating TFs. Since each TF is distinctive, the area requirement varies and therefore the locations identified by the planners sometimes allow to accommodate more than one TF during any project phase and thus the discrete location becomes a continuous area available for the TFs to be collocated.

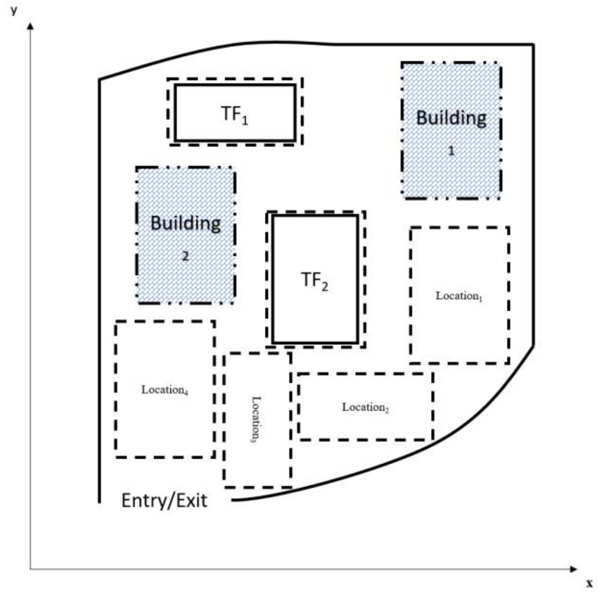

Figure 2. Discrete SLP problem representation.

The studies have indicated some methods to decompose the continuous site space problem to discrete using grid technique whereas this representation still mimics the nature of continuous SLP problem [9]. Although here the approach of using the greatest common divisor (GCD) of the TFs required can help in decomposing the site space into grids [8] as depicted in Figure 3. The TFs are positioned with respect to the cell reference. Such representation restricts irregular shapes of TFs and these TFs are to divided and modelled into a regular shapes [10].

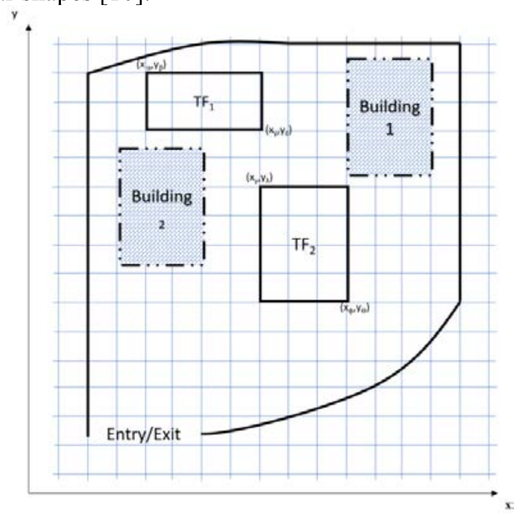

Figure 3. Grid-based SLP problem representation.

Selection of smaller grid size can be a potential solution to the limitation of searching solution between the grid space; but at the same time, it will increase the computation requirements [10], [11]. Considering such computational needs, researchers have targeted optimisation-based approaches for SLP. The mathematical formulation for SLP problem is depicted in equation 1 and Table 1. The formulation presents the weighted sum method of handling multiple objectives of SLP.

$\sum_{i=1}^{n} w_i \cdot f_i(x)$	**Equation 1**

Subjected to multiple constraints for example:

Table 1. Constraints of SLP from literature.

Constraint	**Constraint type [modified from]**
$\sum_{p=1}^{n} \boldsymbol{x_{pl}}$	Positioning constraint [12]
$\lvert x_p - x_q \rvert \geq 0.5\,(\overline{W_p} - \overline{W_q})\mu_{pq}^{x}$ **∀p, q ∈ F:p < q** $\lvert y_p - y_q \rvert \geq 0.5\,(\overline{L_p} - \overline{L_q})\mu_{pq}^{y}$ **∀p, q ∈ F:p < q**	Inclusion constraint [13]
$\lvert CXF_p - CXF_q \rvert - (LXF_p - LXF_q)/2 \geq D_{min}$ Or $\lvert CYF_p - CYF_q \rvert - (LYF_p - LYF_q)/2 \geq D_{min}$	Minimum Proximity constraint [9], [14]

Where, the used notations mean as follows:

Symbols	**Description**
$\boldsymbol{w}$	Priority weight
$\boldsymbol{f(x)}$	Objective function
$\boldsymbol{x_{pl}}$	Decision variable indicating positioning of facility p at location l
$\boldsymbol{x_p}$	Centroid coordinate of facility p in x direction
$\boldsymbol{x_q}$	Centroid coordinate of facility q in x direction
$\boldsymbol{y_p}$	Centroid coordinate of facility p in y direction
$\boldsymbol{y_q}$	Centroid coordinate of facility q in y direction
$\overline{\boldsymbol{W}}_{\boldsymbol{p}}$	Width of facility p
$\overline{\boldsymbol{W}}_{\boldsymbol{q}}$	Width of facility q
$\overline{\boldsymbol{L_p}}$	Length of facility p
$\overline{\boldsymbol{L_q}}$	Length of facility q
$\boldsymbol{\mu_{pq}^{x}}$	Binary variable, equals one when no overlap takes place between the facilities within the same location in x direction
$\boldsymbol{\mu_{pq}^{y}}$	Binary variable, equals one when no overlap takes place between the facilities within the same location in y direction
$\boldsymbol{CXF_p}$	X coordinate of Reference Point of Facility p
$\boldsymbol{CXF_q}$	X coordinate of Reference Point of Facility q
$\boldsymbol{LXF_p}$	Length of Facility p on X Axis Direction
$\boldsymbol{LXF_q}$	Length of Facility q on X Axis Direction
$\boldsymbol{D_{min}}$	Minimum distance between edges of Facilities
$\boldsymbol{CYF_p}$	Y coordinate of Reference Point of Facility p
$\boldsymbol{CYF_q}$	Y coordinate of Reference Point of Facility q
$\boldsymbol{LYF_p}$	Length of Facility p on Y Axis Direction
$\boldsymbol{LYF_q}$	Length of Facility q on Y Axis Direction

Since the SLP problem involves multiple constraints to manage, the computer implemented method of solution search through mathematical modelling are explored in SLP research as they promise solution search faster than human generated layouts.

The literature indicates that the constraints of SLP in the developed mathematical formulations are much lesser than the actual constraints the planners handle in practice [4]. This could be due to the more computational requirements the optimisation model will need with an increase in more constraints to handle. Although the technological advancements at present are capable of handling high computational requirements, the problem of SLP is more about achieving feasible solutions as quickly as possible [15]. Site space decomposition is one way to reach optimal solutions faster than searching in large pool of potential solutions. Thus the literature has suggested methods of transforming continuous SLP problem to a grid based SLP. This transformation minimises the search points to be explored for optimal solution in the formulated SLP problem.

Such geometrical transformation(s) are investigated in this study to identify the possible way for handling the SLP constraints that can reduce the computational requirements for solving the SLP problem in a timely manner.

3 Constraints Typology of Construction SLP

The SLP problem is defined as a spatiotemporal problem, and the spatial and temporal constraints of SLP are handled mathematically in the optimisation-based approach for planning layouts. The developed typology presented in Figure 4 indicates SLP's spatial and temporal constraints. The sub-categories of these two categories highlight the specifics of each constraint modelled in a mathematical SLP optimisation model. These sub-category constraints can further be classified as soft or hard constraints for SLP problem based on the mathematical formulation of SLP. By definition, the hard constraints are mandatory bounds meant to be satisfied with no modification possible to the conditions, whereas the soft constraints provide flexibility in terms of modifications possible to the bound.

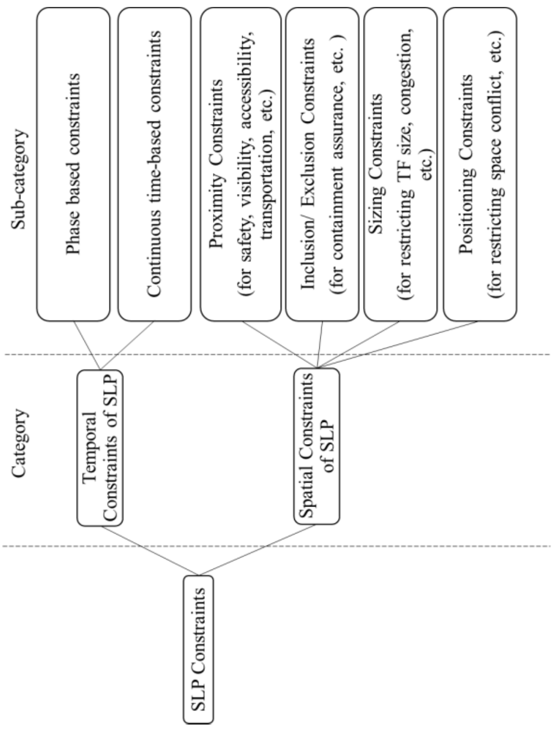

Figure 4. Developed SLP constraints typology.

As like site space, the project duration is sub-divided by researchers in SLP studies into manageable project instances called phases. These phases capture some timeframe of the project duration and are planned for that specific timeframe only. The phased based constraints indicate the need of a TF in a particular project phase and thus the impact of the positioning of TF in preceding phase is not captured on the TF positions in the following phases. Thus to overcome the limitation of phase based SLP the project duration is considered continuous and the impact of positioning TFs on construction site is captured holistically. The category of spatial constraints includes but is not limited to proximity, inclusion or exclusion, sizing, positioning constraints. These sub-categorical constraints encompass multiple bounds necessary for making SLP decisions like the positioning constraints highlight the zoning requirements for facilities and the orientation in which the TFs are to be located. The sizing constraint on TFs helps in restricting site congestion due to large size TFs located on a congested site. It enables planners to limit the required size of TF to accommodate all machinery associated with the TF along with working place available for performing work. Inclusion or exclusion constraints ensure the TFs must lie within the boundaries of the project site and the exclusion bounds can ensure there are no entry or exit blockages for transporting materials on the site [16]. Another constraint to ensure no blockage of quick egress in situations of accident on site is the proximity constraint. This constraint imposes limits to position certain TFs as far or as close as possible to the execution site. All these constraints of spatial nature [17] are modelled as mathematical bounds in the existing optimisation-based SLP studies [16].

The present research targets the spatial constraints of the SLP, and a design driven framework for handling SLP constraints is conceptualised and demonstrated.

4 Conceptualisation of 'Design for SLP'(DfP)

The intangible benefits of SLP are among the reasons due to which the SLP remains unconsidered by the SLP practitioners. As a result the site conditions adverse over time as construction progresses and therefore the existing SLP literature highlights necessity of planning layout as early as possible in a construction project. The planning of layouts requires inputs for making decisions and these inputs are sought either from past projects or assumed based on experiential learnings of the planners. But such approach results in lapses as the past projects do not reflects the challenges associated with current project. Thus this study proposes utilisation of project design for SLP (DfP) by handling spatial constraints through design.

Designing for construction projects requires ideation and enables planners to plan for execution. Therefore, if all required information that aid in planning can be embedded into project designs, more meaningful planning outcomes are expected. In recent years, the SLP researchers have focused on utilising the building information modelling (BIM) for the SLP purposes. The developed BIM models are used for information inputs to the optimisation models for SLP. Primarily the data-based inputs are retrieved from the BIM model and then fed to the mathematical model to generate optimal layouts [18]. This approach presented the advantage of design for site layout planning (DfP), where BIM provided the necessary quantitative information for layout generation.

This study demonstrates the feasibility of handling constraints through design and the advantage of DfP. An example BIM model is prepared where two industrial buildings as shown in Figure 5 are to be constructed. The proposed pathways for vehicular movement are identified and marked, leaving out seven potential areas for TF allocation depicted as shaded regions. These shaded regions are the result of continuous site space divided into regions due to the road network. Though the representation appears discrete, but the regions represent continuous site space where single region can accommodate more than one TFs.

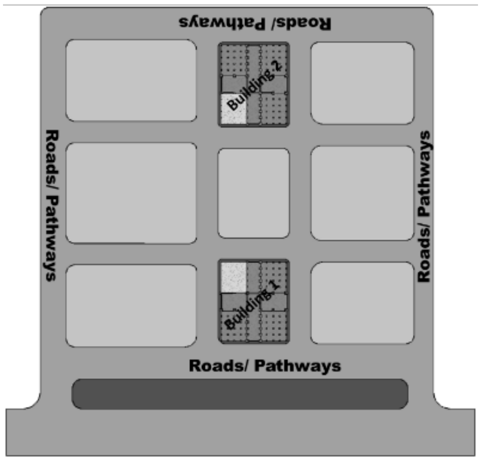

Figure 5. Test case model representation.

The necessary TFs required for the project are identified and required area for accommodating individual TF is mapped in the project design along with the project information. Identifying the area requirement for TFs might appears as an additional task for planners but this is part of the existing SLP practice [19]. Apart from the traditional regular shapes for TFs, the area for consumables can also be mapped in irregular shapes as shown in Figure 6. The shaded area around the location area demarcates the safety zone created as part of the location area for TF to consider the ***proximity constraint*** of the TFs.

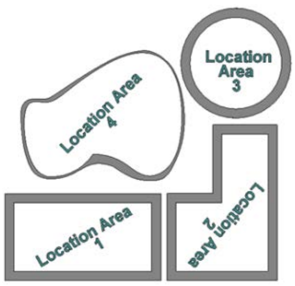

Figure 6. Area requirements for TFs with safety zone modelled as part of the location area.

Along with mapping of area requirements of TFs the whole site area is distributed between 100x100 grids of equal spacing using the GCD method demonstrated in existing SLP studies [20]. Each grid point within the site area as shown in Figure 7 represents a solution for locating a TF.

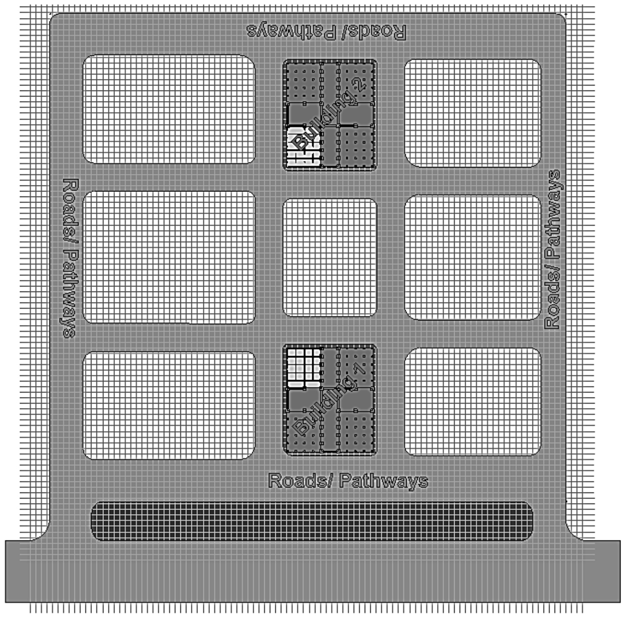

Figure 7. Transformed the test case model to grid-based representation.

Although these 100x100 grid points are possible positions but does not qualify as feasible solutions, and by definition the solutions satisfying the constraints of the problem are feasible solutions [21]. In the considered case the imposition of inclusion constraint will limit the positioning of TFs outside the boundary of the project site resulting in reduction in the number of solutions for exploration in the solution space by eliminating the grid points closer to the site boundary. This research presents a test example to understand this reduction in the solution space through a design based spatial constraint handling approach for SLP.

4.1 Search space decomposition through spatial constraints of SLP

As demonstrated above that how the inclusion constraint of SLP can decrease the number of possible solutions a test case is developed where a TF area requirement of 450 square units is considered. Since the shape of the TFs can vary during the due course of project progress the 450 square units of area is modelled proportionately into eight combinations listed in Table 2 but as a regular shape area shown in Figure 6 as location area 1.

Table 2. Considered TF area dimensions and respective feasible position count.

Sr. no.	Site area dimensions (Length x Breadth)	Orientation	Feasible positions (Count)
1	45x10		27
2	40x11.25		194
3	35x12.857		519
4	30x15		870
5	25x18		1143
6	20x22.5		1296
7	15x30	Serial no. 4 (rotated 90^o)	1244
8	10x45	Serial no. 1 (rotated 90^o)	559
Total			5852

The choice of regular shape is driven by motivation to demonstrate the functionality through different dimensional variations. Whereas in case of irregular shape the flexibility to iterate through different design variations will result in higher complexity. The Table 2 also reports the results of feasible outcomes from the possible 8x100x100 outcomes when the location area 1 for a TF is taken through all the grid points and the spatial constraints mentioned in Figure 4 are imposed. The location area 1 is dimensionally transformed into different variations to indicate the influence of the ***sizing constraints***. Firstly the ***inclusion constraints*** are imposed to ascertain the TFs are being positioned inside the boundaries of the site. Following the inclusion constraints, the ***exclusion constraints*** are considered. It helped in ascertaining the non-overlapping of the TF area with the road networks and the upcoming buildings as shown in Figure 8. The grid positions resulting in such violations are removed from the solution pool of the optimisation model to reach optimal solutions faster.

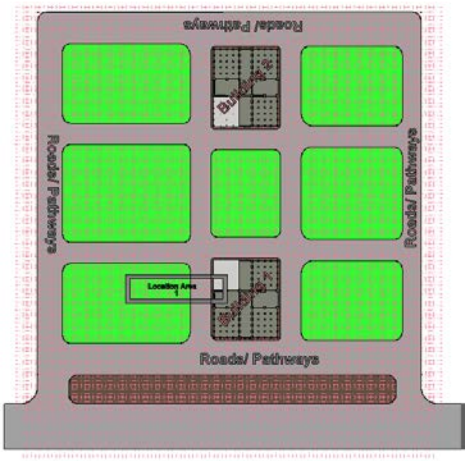

Figure 8. Inclusion constraint satisfied with violation of exclusion constraint.

The imposition of the spatial constraints resulted in 92.6 percent reduction of feasible solution count by eliminating the unfeasible positions through design for the considered case. The studies targeting algorithm based location decomposition for SLP has highlighted that the approach of reducing the solution search area through eliminating infeasible solutions from the solution pool for SLP problem results in generating layouts in timely manner [21]. Similar thrust has been observed in construction safety studies, where the planners were not able to identify the tangible benefits associated with maintaining safety on construction site and consequently numerous incidents had been reported resulting in prevention through design a key research area of construction safety management [22]. This study proposes a concept 'Design for SLP' (DfP) that is similar to 'design for occupational safety and health' (DfOSH) [23], [24]. As like DfOSH, Prevention through Design (PtD) and other design for safety related concepts DfP also advocates for a shared responsibility among project stakeholders for layout planning [23]. These design-based approaches for mitigating safety risks underpin the advantages of proactiveness during project design phase resulting in project success. Although the influence of design is captured in the safety-related domain [25], the design influence on SLP is under explored in the SLP research.

5 Entailments from the proposed DfP

The modelling of TFs for construction projects is not a common practice but doing so will help in managing the project and site workflows. These modelled TFs will be useful in calculating the area requirement of TFs for a project. Such consideration of area requirement of TFs though appears as an additional work but after preparing for a number of projects will result in a database of TFs required for projects and their area requirements will be a data asset for the organisation. The utilisation of BIM will enable the construction organisations to use the modelled TFs and area requirements for further projects and overtime the database will be enriched significantly that the need for modelling TFs and the area requirements will diminish. The approach of handling the SLP spatial constraints through design as presented in this study offers the search area reduction for the mathematical approach for SLP. Notably, the capture of constraints through design has transformed the solution search space for the mathematical model into a discrete solution search space as depicted in Figure 9.

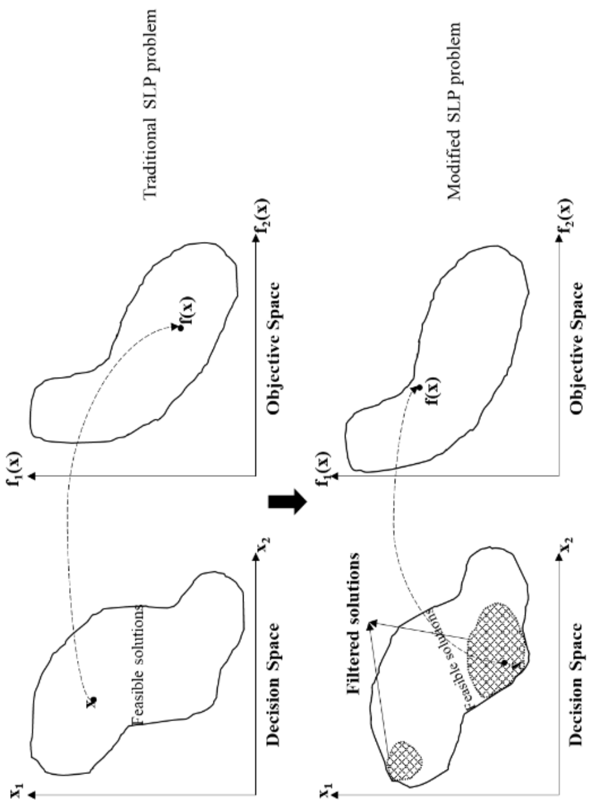

Figure 9. Transformation of traditional SLP to design-based SLP.

The handling of spatial constraints through design though reduces the solution search space but poses another challenge in form of identifying the mathematical algorithms that can help in solving the discontinuous SLP optimisation problem and provides an interesting area of further research. Also a single TF layout is attempted in this test case whereas multiple TF layout is possible using the methodology presented in the study.

6 Conclusion

Traditionally the problem of SLP is considered as decision making problem and is attempted to be benefitted through optimisation models. Although the optimisation models provide mathematical approach to handle the constraints of real-life scenarios, there exist challenges in modelling them. Therefore this study attempted to handle the constraints of SLP through design. In attempt to do so the SLP constraint typology is developed, and the spatial constraints are identified to have features that can be modelled as part of the project design and then the BIM design is put to use for handling the spatial constraints. The presented approach is limited to regular-shaped single TF with variation in dimensions, but the demonstrated case provides evidence of applicability for TFs of different shapes and sizes. The study highlighted the opportunity of utilising design-based constraint handling in SLP problem where visually verifiable results are expected to be generated. The presented workflow for handling SLP constraints filters out the infeasible solutions from the pool of possible solutions to the SLP problem. The optimisation models for SLP are expected to benefit from this study due to reduction in solution search space and to provide optimal solutions to the problem of SLP in a timely manner. The study provides an opportunity for further research focusing on algorithms for SLP optimisation to search in discrete solution search space.

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