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GIS-based dynamic construction site material layout evaluation for building renovation projects

Xing Su [a,1], Abdul rahman Andoh [a,2], Hubo Cai [a,*], Jing Pan [b,3], Amr Kandil [a,4], Hisham M. Said [c,5]

[a] Division of Construction Engineering and Management, School of Civil Engineering, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, United States
[b] Department of Building Construction Management, College of Technology, Purdue University, West Lafayette, IN 47907, United States
[c] Department of Civil Engineering, Santa Clara University, Santa Clara, CA 95053, United States

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ABSTRACT

Material layout is critical in construction planning. A poor material layout causes site congestions and the inaccessibility of certain materials, leading to project delays and cost overruns. Site material layout is mainly constrained by space and time that have to be considered in an integrated manner, which is very limited in the existing literature, particularly for building renovation projects that are typically constrained by a tight space. This study proposed a new concept, e.g. Material Accessibility Grade (MAG), to quantify the material accessibility throughout the project duration. A material layout evaluation model (MLEM) was created based on the MAG concept to integrate space and time. The MLEM was implemented on a Geographic Information System (GIS) platform and applied in a building renovation project. It was found that besides plan assessment and comparison, the MLEM could also detect spatial–temporal conflicts and suggest mitigation measures to improve material accessibility and reduce time waste.

1. Introduction

Construction site space is a limited resource that is as important as other resources such as money, time, material, labour, and equipment [1]. Inappropriate site layout planning could cause unnecessary time spent due to site traffic congestion, labour inefficiency, and even repositioning materials or temporary facilities. Sanders et al. [2] stated that congested workspace and restricted access account for up to 65% and 58% loss of efficiency, respectively.

Space planning and management is a key component in construction site materials management. Kini [3] defined the objective of site materials management to be ensuring that the materials are available when required to meet the construction schedule. The word “available” still leaves some room for clarification. Considering the critical roles of space and time, the objective of site materials management is more appropriately elaborated as to ensure that materials are accessible on site and are able to be delivered to the working spot without extra time or equipment cost (i.e. repositioning other materials or temporary facilities) when required. Consequently, site material layout planning can be treated as a challenge of maximizing the accessibility of materials with regards to handling and delivering throughout the project duration.

Material accessibility is especially critical to building renovation projects in urban areas. These projects are typically constrained with a limited site area and an ongoing building occupancy. Fig. 1 illustrates an example that the lay-down area, staging area, and site storage area are combined to save space. The storage area may be close to working spots or workshops but the path between them is narrow and sometimes even blocked by vehicles. In this situation it will take much more time to reposition the material if space conflicts happen or material is not accessible (i.e. path is blocked). Despite its importance, material layout planning for such projects has not received adequate due attention because of their short project durations and low budgets. Presently the material layout planning for this type of construction projects, in most cases, is based upon the superintendents' personal experience and knowledge, taking a “first arrive, first serve” manner [4]. Without a user-friendly, computer-based site layout planning system, superintendents usually describe the spaces they need generically using qualitative positional descriptions [5], which is error prone in aspects of planning and communication, leading to material accessibility problems during construction.

In order to effectively address the material accessibility challenge in building renovation projects, it is important to understand their unique characteristics summarized below.

- Material lay-down and staging areas are typically combined to save space with no clear boundaries;

* Corresponding author. Tel.: +1 765 494 5028; fax: +1 765 494 0644.
E-mail addresses: xsu@purdue.edu (X. Su), aandoh@purdue.edu (A. Andoh), hubocai@purdue.edu (H. Cai), pan8@purdue.edu (J. Pan), akandil@purdue.edu (A. Kandil), hsaid@scu.edu (H.M. Said).
1 Tel.: +1 765 418 4331; fax: +1 765 494 0644.
2 Tel.: +1 765 494 2240; fax: +1 765 494 0644.
3 Tel.: +1 765 494 2459; fax: +1 765 494 0644.
4 Tel.: +1 765 494 2246; fax: +1 765 494 0644.
5 Tel.: +1 408 551 7156; fax: +1 408 554 5474.

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Fig. 1. A building renovation project site.

- After being unloaded from transporting vehicles, materials rely on human labours for future delivery during building renovation. A safe and wide enough access path is essential; and
- Time is critical because of the fast pace of material consumption and short project duration. There might be materials being used up and coming in on a daily basis.

The above unique characteristics of building renovation projects differentiate them from large scale, new construction projects and thus, the typical objective of minimal travel distance or transportation cost in optimizing construction site layout as suggested in previous studies [1,6–8] might not be appropriate for building renovation projects. Thomas et al. [9] identified that, for a small site, travel distances and transportation costs may be of secondary importance while labour safety, adherence to the project schedule, and good productivity may be of the primary importance.

The study presented in this paper proposed three main criteria in evaluating material layout plans to be: (1) a large enough space to store and pick up a material, (2) a wide enough path to deliver the material from the storage area to the working spot, and (3) a short delivery distance. This study also created Material Accessibility Grade (MAG) to integrate these three criteria into a single overall measure for material site layout plans. A GIS-based Material Layout Evaluation Model (MLEM) was developed to quantitatively measure the MAG of a given layout plan and compare different layout plans based on their MAG values. This in turn, forms the base for optimizing site material layout planning with regard to the material accessibility.

2. Related studies

A number of construction site layout studies have been conducted to optimize the allocation of site space to meet the space needs for material storage and on-site prefabrication and assembling [10,11]. The focus has been the two-dimensional (2D) space needs of temporary facilities at specific time points and the optimization of site layout with regard to the total travel distance (cost) among temporary facilities [11–13]. Artificial intelligence (AI) methods such as the knowledge-based systems [14–18], neural networks [19], mathematical optimization [20], and genetic algorithms [1,6–8,21–25]; have been applied to optimize site layout by minimizing the total travel distance (travel cost) among temporary facilities. These studies considered site layout planning at an area level, i.e., a site was divided into a working area, a storage area, and a lay-down area and each area was modeled as a single areal object.

A critical factor that might affect the total travel distance is the material delivery path. Two temporary facilities of *A* and *B* might be close to each other with a short distance of *d*. But without a clear passageway, the travel distance for delivering materials between *A* and *B* requires a "detour" that could be much larger than *d*. Recognizing its importance, the material delivery path has been treated either as an individual type of construction site space [26] or as a part of the construction task execution space [27], both at the areal level. However, this areal level, aggregate approach might not be adequate in dealing with more complex scenarios in which, the type of materials being handled matters. For instance, there is no adequate passageway between *A* and *B* for material *M1*; but there is an adequate passageway for material *M2*. Consequently, the site layout planning must be detailed down to the material element level so that material-specific factors including the delivery path and the convenience of handling could be incorporated.

Solving the material layout problem for congested sites requires intensive calculation and analysis in both spatial (i.e. site dimension, path width, and storage area dimension) and non-spatial (i.e. material storage life cycle and material properties) aspects. Given its unique merit in seamlessly integrating spatial and non-spatial properties, GIS appears to be a promising tool in assisting site layout planning. For instance, Cheng and O'Conner [28] used GIS to automate site layout for construction temporary facilities. Cheng and Yang [29] developed a GIS-based cost estimating system that was integrated with material layout planning. These studies have proved GIS to be a powerful tool for spatial–temporal analysis in material site layout planning and optimization.

From a practical perspective, Winch and North [27] interviewed 18 experienced site planners, conducted an extensive literature review about construction space scheduling, and concluded that any space scheduling system should bare the following features: (a) it should be a decision-support system instead of a decision-making system; (b) it should be compatible with existing applications and methods in use by planners (which is called process integration); and (c) the use must be quick and intuitive. An easy-to-use material layout evaluation system with high compatibility shall have the great potential of industrial adoption and this is the philosophy that guided the development of the GIS-based MLEM in this paper.

3. Contributions

The study presented in this paper introduced a new measurement index (e.g. MAG) to quantitatively measure site material layout plans based on three criteria of material pick-up, passage way, and delivery distance. A GIS-based MLEM was developed with a set of tools to automate the evaluation of MAGs of given material layout plans through the project life, forming the base for optimizing site layout plans. The user-friendly computer tools associated with the MLEM are expected to facilitate the adoption of this system by the construction industry.

4. Methodology

A GIS-based MLEM was developed to automate the assessment process of the material layout plan provided based on the user's knowledge and experience. Fig. 2 illustrates its framework, in which the MLEM takes Material Schedule, Material Layout, Site Drawings, and Construction Schedule as inputs and generates Material Demand and Material Supply in terms of what (materials), when, where, and how many.

Information about material demand is extracted from the site drawings and the construction schedule. The GIS-based MLEM converts the site drawings into polygons to represent the total site area, the permanent facilities, and the working spots. Users will be asked to confirm the shapes of the site and the permanent facilities, and to mark the working spots to indicate where the materials need to be delivered. The construction schedule is required to contain material information, e.g. each construction activity in the schedule is expected to have the information about the name and the quantity of the required materials. Besides, three attributes are obtained from the construction schedule and linked to each material: "Using Time" (UT)—the time from when the material is being used (corresponding activity starts); "Ending Time" (ET)—the time from when the material has been used up or moved out (corresponding activity ends), and "Quantity Demand"—the amount required by the activity. The GIS-based MLEM generates a table of materials (or, bills of materials) stores all the information as the materials' thematic attributes.

Information about material supply comes from the material schedule and the material layout plan made by the user. The material schedule specifies material attributes such as "Name"—what materials will be purchased, "Quantity Supply"—how many they are, and "Starting Time" (ST)—when they will arrive on site. With a material table containing all the necessary attributes, the user is promoted to assign each material a certain storage area on site. A "Material Layout" layer is generated to serve as a drawing canvas for the user's sketch, with a floating window displaying materials' attributes to assist decision making. The geometry and location information of each material is hereby obtained.

In addition to taking inputs from users and generating material supply and demand information, the MLEM consists of three analysis modules: *Quantity Check*, *Conflict Detection*, and *MAG Evaluation* to be executed sequentially. The *Quantity Check* and *Conflict Detection* modules check the feasibility of a given plan. The *Quantity Check* module is executed following the generation of the table of material. Any material with its "Quantity Demand" greater than "Quantity Supply" will be reported. The *Conflict Detection* module detects space conflicts on delivery paths and initiates the request for modifying the site layout plan and the Construction Schedule till reaching a conflict-free plan. The

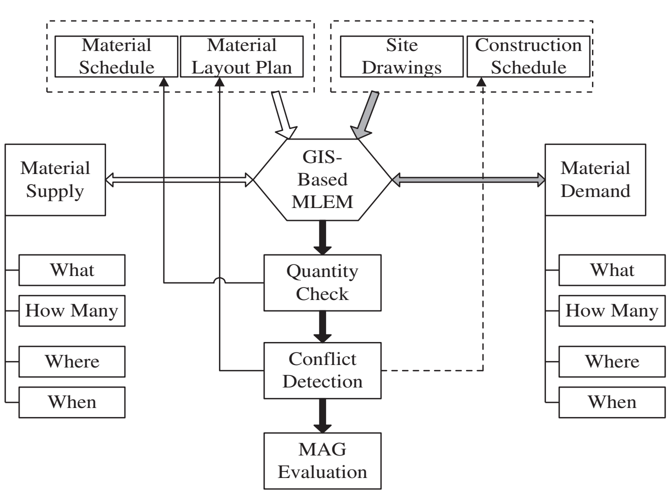

Fig. 2. The framework of the GIS-based MLEM.

MAG Evaluation module calculates MAG scores for all conflict-free plans. These scores are then compared to maximize the material accessibility.

The GIS-based MLEM has a few assumptions including: (1) the storage area has no height constraint and the system works in a "2D + time" environment; (2) material overlap is not encouraged (an exception is discussed in Section 6); and (3) each block occupied by a material pile is in the shape of a square or a rectangle.

4.1. Material accessibility grade (MAG)

The MAG refers to the accessibility of an on-site material at a certain day. It is calculated as the weighted total of three criteria multiplied by the travel frequency, illustrated in Eq. (1).

$$\mathrm{MAG} = (\lambda_1 x_1 + \lambda_2 x_2 + \lambda_3 x_3)^* f \qquad (1)$$

Where x_1, x_2, and x_3 are the Grade of Pick-up Convenience (GPC), the Grade of Delivery Convenience (GDC), and the Grade of the Shortest Path (GSP), respectively; λ_1, λ_2, and λ_3 are the relative weights; and f is the travel frequency.

4.1.1. Grade of pick-up convenience (GPC)

The pick-up convenience is affected by the size of the material unit and the opening of its storage area. The GPC is a measure of how convenient it is to handle the material, i.e. bring it out of its storage area. It is calculated as the ratio of the Open Length (*ol*) to the Critical Length (*cl*) in the range of 0 to 2 (Eq. (2)). A larger GPC indicates a greater convenience in picking up a material. The upper limit is set to 2, an empirical number based on field crew's experience to indicate that when the convenience ratio reaches 2, further increasing the ratio does not benefit the pick-up convenience anymore. The Open Length, or *ol*, is the total length of unblocked sides. The Critical Length, or *cl*, is the minimal length required to handle the material. It is by default the maximum dimension of a unit of material with exceptions applicable to materials such as steel bars, pre-fabricated beams and columns, and pipes. For instance, it does not need an open side with a length equals to or greater than the length of a steel bar to move it out. In this case, the maximum length of its cross section is set to be the *cl*. The concept of "a worker's comfortable working range" is introduced herein to represent the minimum width (customizable with a default value of 0.9 m) that allows a worker to pick up a material or carrying the material without danger or inconvenience. The actual value of *cl* used in Eq. (2) is the larger of the "worker's comfortable working range" and the critical dimension identified for a specific type of material. When implemented in GIS, users are informed about the default values being used and are recommended to customize such values per their discretion.

$$x_1 = \begin{cases} ol/cl, & \text{if } ol/cl \le 2 \\ 2, & \text{if } ol/cl > 2 \end{cases} \qquad (2)$$

Fig. 3 provides a simplified example to illustrate the calculation of *ol*, *cl*, and x_1 (GPC). For material A, its *cl* is 0.9 m, the larger value of the default worker's comfortable working range (0.9 m) and the maximum unit length of material A (0.5 m). The *ol* is 4 m as the length of the bottom side, the only side that is not blocked. Similarly, values of *ol* and *cl* of materials B and C can be calculated as: $cl_B = 1$ m, $ol_B = (5-4)+5+(5-2.5) = 8.5$ m, $cl_C = 0.9$ m, and $ol_C = 2.5$ m. The GPC for all three materials is 2.

4.1.2. Grade of delivery convenience (GDC)

GDC is determined by the width of the delivery path. Spatial operations and raster-based calculations in GIS are employed to calculate GDC and GSP in this study. Fig. 4 provides an example to illustrate the process of deriving a raster Path Map from a raster Storage Map that is derived from a raster Site Map via raster-based calculations. A complete site material layout is originally a vector data layer in which, the

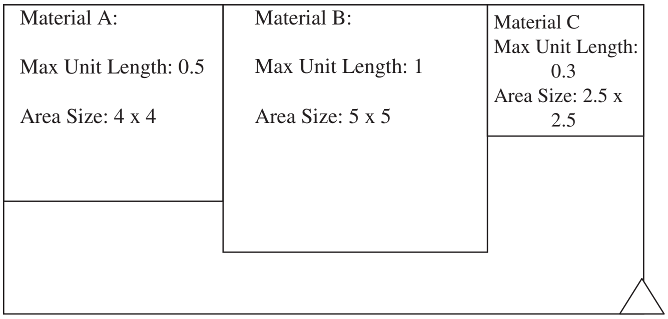

Fig. 3. A simplified illustration of the open length and critical length (unit: meter).

site and material storage areas are all polygons. For each material unit, a raster "Storage Map" is generated by rasterizing the original vector map with the cell resolution set at a third of its *cl*. Cells in the resulting Storage Map have a value of 0 or 1. If a cell is occupied by any material, its value will be 0 to indicate that this cell cannot participate in a path; otherwise it will be assigned with a value of 1. A raster Path Map is then derived from the Storage Map via a neighborhood analysis. Each cell in the Path Map is assigned a value of the summation of its eight neighbors and itself. This intermediate Path Map is further processed via a cell-by-cell operation by multiplying it with the Storage Map to exclude those occupied areas from the potential areas for the delivery path, i.e. zeroing out those cells that contain a value of 0 in the Storage Map). The value of each cell in the resulting final Path Map indicates the grade of passability of a material through this area. Since the side length of each cell is one third of the material unit's *cl*, a cell with a value of 9 ($3*3$) can be interpreted as such that the material unit could pass without any impediment. A path composed of cells with a value of 9 could serve as the delivery path with great convenience.

Cells that touch the origin and the destination will never have a value of 9 because they touch the boundary. Taking this into consideration, the path searching algorithm in this study starts with a "pseudo-origin" determined as below:

1. Buffer the origin with a radius of 2/3 (two thirds) of *cl*;
2. Identify Path Map cells that completely fall inside the buffered area;
3. The cells with a value of 9 are stored as the "pseudo-origin."

A similar procedure can be followed to determine a "pseudo-destination" for the path searching algorithm. The Path Map in Fig. 4 underscores the resulting cells for "pseudo-origin" and the "pseudo-destination" with thick boundaries. Using a radius of 2/3 of *cl* ensures

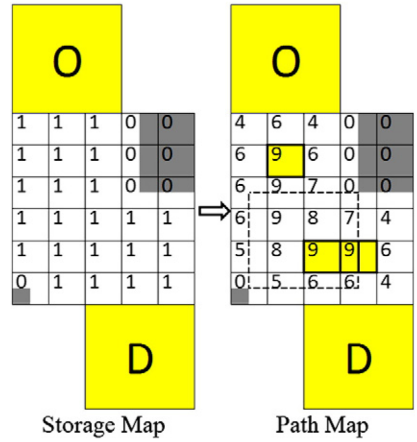

Fig. 5. Identification of the available path.

that the resulting cells are the closest ones which could possibly have a value of 9.

A cell with a value less than 9, however, may not necessarily block the way due to the existence of "margin areas". An example is provided in Fig. 5. No path of all cells with a value 9 exists between the "pseudo-origin" and the "pseudo-destination." Yet a material unit may pass cells with a value of 8 with some inconvenience. When the smallest value of a path is 7 or less, the path is either blocked or has its delivery convenience greatly affected. The effect of the "margin areas" could be reduced by adopting higher cell resolution, i.e. 1/9 of *cl* instead of 1/3 of *cl*, but the computing load will increase exponentially.

Based on the previous discussion, this study calculates GDC as below (Eq. (3)). When GDC equals 0, it implies a possible spatial conflict. This information is passed to users and initiates a modification of the Material Layout Plan. The GSP and the MAG will be only calculated for conflict-free layout plans.

$$x_2 = \begin{cases} 2 & \text{when the minimum cell value in the selected path} = 9 \\ 1 & \text{when the minimum cell value in the selected path} = 8 \\ 0 & \text{when the minimum cell value in the selected path} = 7\,\text{or less} \end{cases} \tag{3}$$

GDC and GPC all use *cl* as the most important factor, which refers to the length of a material unit defined by user. This critical length information determines the space need in the process of picking up a unit of material from its block and delivering it to its destination. The current MLEM has a default set of *cl* values that are determined

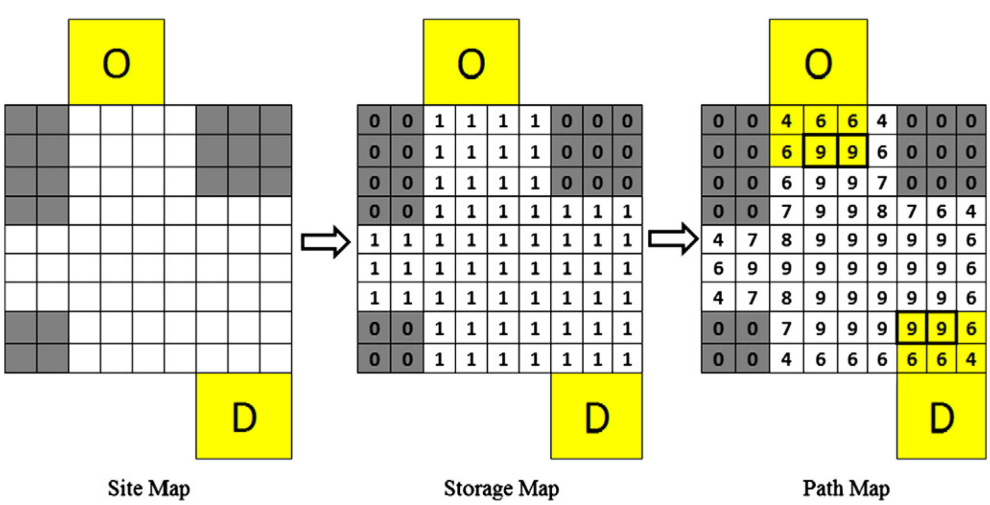

Fig. 4. From a site map to a path map.

based on the general movement characteristics of each type of materials. This default set can be modified to fit specific user needs. For example, the default value of *cl* for RTF bars is set to be the default labour's working range (0.9 m). Such a setup guarantees the minimum space required by one labour to move out a RTF bar. Setting the *cl* value larger, for instance, to be a half of the RTF bar length, guarantees that the bars can be transported by two labours holding bar ends in most cases.

4.1.3. Grade of the shortest path (GSP)

The shortest path (SP) is calculated based on the Site Map and the Path Map. To offset the travel distance within the material storage block, the length of SP equals the path length plus half of the storage block diagonal length. The shortest path algorithm in GIS, which works with a raster that stores the travel cost information as the cell values [30], is adopted in this study. Fig. 6 illustrates the identified shortest path for the same example that was used in Section 4.1.2. The priority is given to cells with a value of 9. Cells with a value of 8 will only participate in the search if no path can be found using value 9 cells.

This study calculates GSP as below (Eq. (4)).

$$x_3 = \begin{cases} 2^{\frac{SD}{SP}}, & \text{if SP} > \text{SD} \\ 2, & \text{if SP} \le \text{SD}. \end{cases} \tag{4}$$

Herein SD represents a standard distance. It can be considered as a threshold value from which the delivery distance starts to significantly affect the productivity. A properly defined SD can avoid the bias that might be given to site layout plans that place materials extremely close to their destination. The default value of SD is set to be a third of the "Max Distance of Site," using a rule of thumb. It is also customizable to adapt to different site layout conditions. The "Max Distance of Site" is measured from the furthest possible point to the destination on site.

4.1.4. MAG as a material handling convenience measure

The three components of MAG, namely GPC, GDC, and GSP, are balanced in the aspect of value range. GPC values are in the range of (0, 2); GDC values can be 0, 1, or 2; and GSP values are in the range of (1, 2). The GDC value of 0 signals a space conflict and therefore, this study adopts a two-step approach. Whenever a space conflict is detected, the users will be alerted and advised to modify the plan. The MAG for a site layout plan will only be calculated if no space conflicts exist. The weights λ_1, λ_2, and λ_3 are overall scalars that correspond to the relative importance of the three components in determining the MAG. The travel frequency f for each material defaults to 1, but could be modified by the user to incorporate the travel frequency into MAG calculation and site layout assessment.

The overall MAG value for a single layout plan does not imply the convenience itself, but mainly serves as the base for comparing with alternative plans for the same project. For a given project with several layout plans under consideration, the larger the MAG value is, the better a specific layout plan is in the aspect of material accessibility. However, the MAG might not be appropriate to serve as the single optimization objective. The storage space and delivery path compete with each other due to limited site space, but the delivery distance does not show a clear linear relationship with either the storage space or the delivery path. The time dimension also remarkably increases the complexity of overall optimization. The two-step approach mentioned earlier guarantees a conflict-free material site layout in step 1 and then objectively chooses a better layout based on step 2 results from alternative layouts.

4.2. Site layout modeling

Every construction site is dynamic. This is particularly true in building renovation projects as they progress rapidly. The time dimension is introduced into this model in a discrete manner with "day" as the basic unit. Based on the input information, three buckets of data are formed:

ST (Starting Time) = {st_1, st_2 … st_n},
UT (Using Time) = {ut_1, ut_2 … ut_n}, and
ET (Ending Time) = {et_1, et_2 … et_n}, where n is the maximum material index.

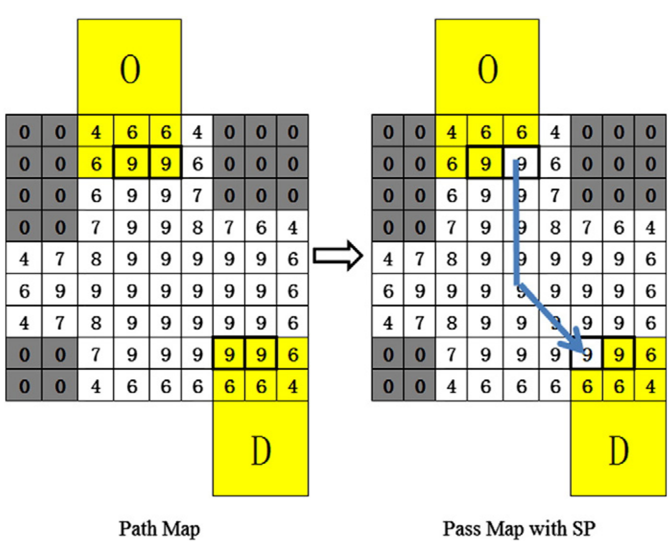

Fig. 6. An example shortest path searching.

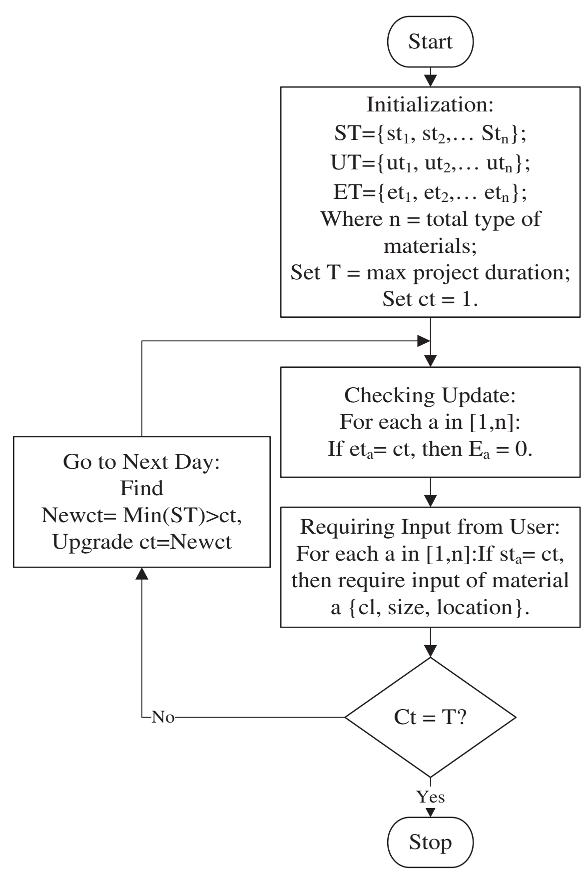

Fig. 7. The flowchart of reading user inputs.

The dynamic nature mainly affects two tasks: obtaining layout plan from user and MAG evaluation. Fig. 7 shows the algorithm of automating the process of obtaining the user's layout plan. On every {$st \in ST$}, there will be a new type material added to the Site Map. The previous assigned materials that have not been used up will be displayed on the map as blocks. If *ct* is denoted as the "current time" and it is less than *et*, then the area occupied by the blocks is not available for any new material. For those materials that used to be on site but have been consumed ($ct \geq et$), the areas occupied by them become available for new materials arriving on site. This material status change is reflected by employing a variable E as a flag to represent its existence, which is determined as below:

$$E = \begin{cases} 1, & \text{when a material exists on site} : st \leq ct < et; \\ 0, & \text{whenamaterialisusedup} : ct \geq et; \end{cases} \quad (5)$$

This process ensures that an updated site map is graphically presented to the user every time the user is prompted to assign a storage block for a material.

The MAG evaluation consists of an outer duration loop and an inner material loop. Fig. 8 illustrates the flowchart of the MAG evaluation algorithm. The duration loop steps through the project duration daily. Specifically, for every {$ut \in UT$}, MAG is evaluated. The resulting MAG value is only kept to the first *st* or *et* after *ut* because a newly added material or consumed material may change the value of the previous MAG. For example, five material piles A to E with their [*st*, *ut*, *et*] being A: [1,1,5], B: [1,1,4], C: [1,2,4], D: [2,2,4], and E: [4,4,4] result in ST = {1,1,1,2,4}; UT = {1,1,2,2,4}; and ET = {5,4,4,4,4}. On day 1, material A and B need to have their MAGs evaluated because they are both used on day 1. On day 2, material D arrives and changes the site layout (ST [4] = 2). The existing MAGs of A and B are stored as old values and new MAGs need to be calculated. On day 3, MAGs of A and B calculated on day 2 can be directly used because there is no new material arriving or being used up after day 2 (all $et > 3$). The material loop is inside an individual step of the duration loop. It calculates the MAGs of all materials on a particular day. The space conflict detection function is embedded into the daily MAG processing block. The two-step approach is enforced by terminating the MAG evaluation process whenever a space conflict is detected (e.g. $x_2 = 0$). The nature of the detected conflicts and potential solutions are communicated to the user to guide her on making corrections/modifications to avoid the conflict.

4.3. System architecture

The model was implemented in a Windows environment on the platform of ArcGIS 9.3. Microsoft Project was used to provide project schedule input. The User communicates with the system through a custom interface developed using VBA under ArcGIS. Fig. 9 shows a

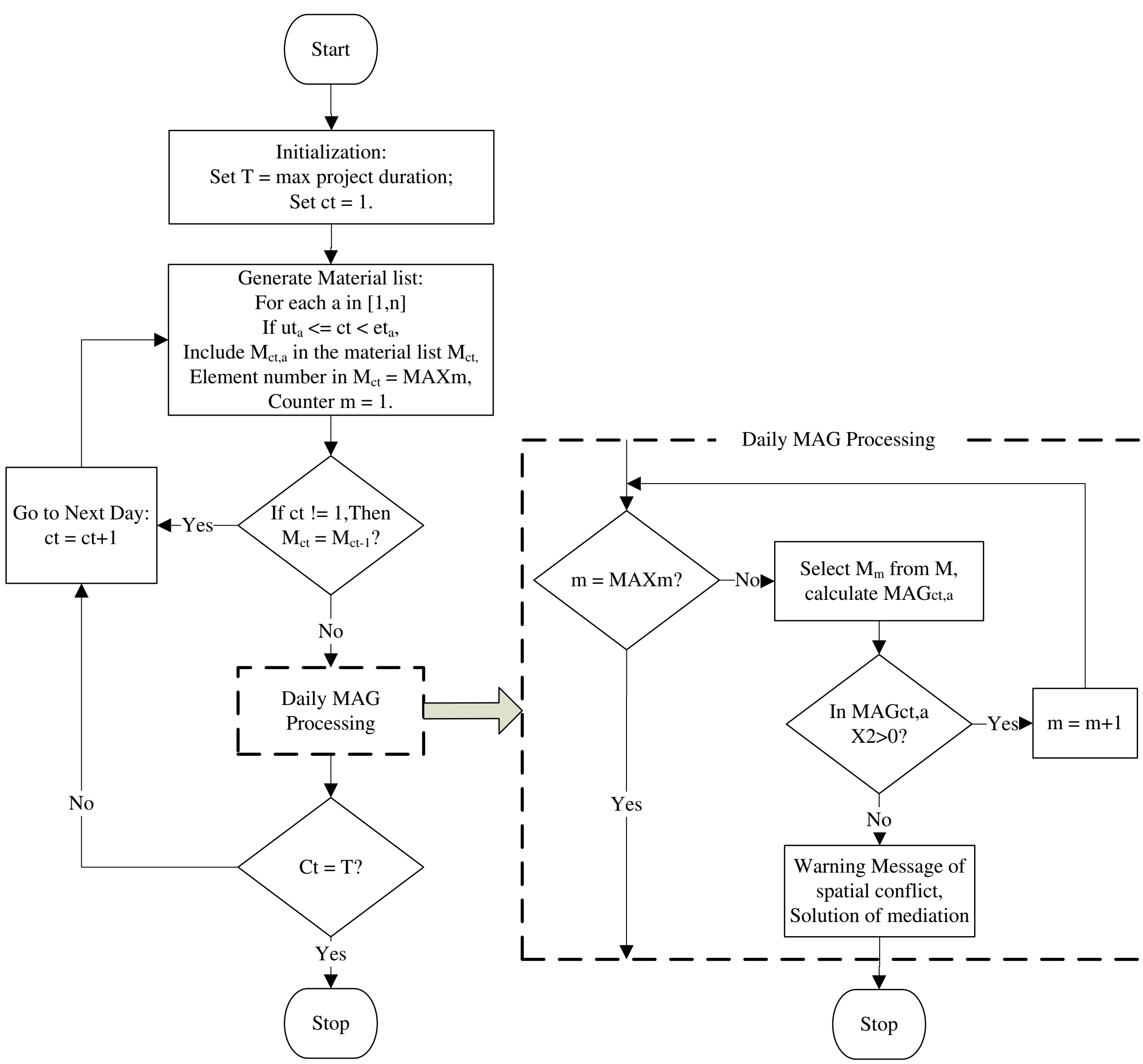

Fig. 8. The flowchart of data analysis.

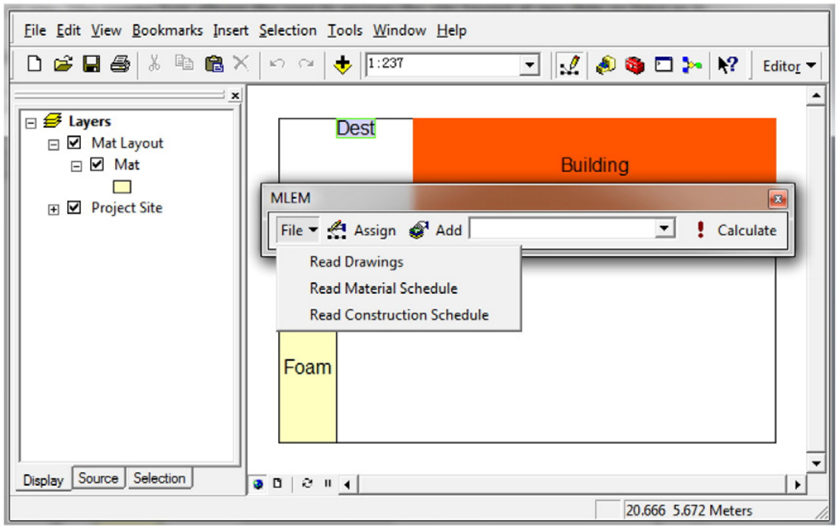

Fig. 9. A screenshot of the GIS-based MLEM.

screenshot of the user interface. There are two existing layer groups: "Project site" and "Mat layout". "Project site" contains the shape of the storage site and the location of the working spot and destination spot. "Mat layout" serves as the canvas and allows the user to draw, move, and delete material blocks. The MLEM tool bar contains a menu, three buttons, and a combo box. The menu "File" is comprised of three functions: "Read Drawings", "Read Material Schedule", and "Read Construction Schedule". The "Assign" button starts the process of getting the user's input for each material's geometry and location. The user draws each block of material with the assistance of a floating window showing all the material attributes including *st*, *ut*, *et*, *cl*, λ and quantities. If there are multiple destinations, the user will be asked to assign each material to its corresponding destination. The "Add" button enables users to place additional material blocks on the site. The combo box allows the user to review the site layout at any date as long as it has been defined. The "Calculate" button processes the data analysis phase after getting all the necessary input information and the output is either a detected conflict or an overall MAG score if there is no conflict.

5. Case study

The implemented system was tested in a laboratory renovation project on the West Lafayette campus of Purdue University. The time period was from September 2010 to December 2010, during which the project has both indoor and outdoor works. The site superintendent planned the material site layout without using the MLEM. The material accessibility evaluation was conducted for a representative time period from November 16th to November 18th to illustrate the working mechanism of this model.

The original site layout in the MLEM interface on November 16th, 2010 is displayed in Fig. 10. The overall site is a 26 m $*$ 17 m rectangular area. There were 9 material blocks assigned on site to simulate the real site condition. Each material block occupies a rectangle area, and has four critical attributes of *cl*, *st*, *et*, and *ut*. The "Building" polygon represents the laboratory being renovated and is treated as a permanent facility here. The "Dest" polygon represents the door to the renovation building and serves as the destination here. The indoor area is comparatively small and empty and therefore, further delivery from the door to the real working spots is not considered. The outdoor work is demolition and no material is required. The white area is the passage way and the site entrance is located on the right side.

The attribute table of the materials is listed in Table 1 (the quantity attributes are hidden). The renovation work actually started from November 15th. Before that date, some site preparation and cleaning work had been conducted.

On November 17th, the demolition work started and a wheel loader was on site to hold the cement slab cut off from the building (Fig. 11). This work lasted around 7 h. Fig. 12 illustrates the updated site layout on that day.

Meanwhile, the indoor renovation work needed "Gravel Box" and "Tool". The model checked the "Gravel Box" and the "Tool" in conflict detection because the logical expression of $ut <=$ current date and $et >$ current date was evaluated to be true. Since the "Tool" is located right next to the destination, this example focused on the "Gravel Box" and detected a space conflict, e.g. the "WheelLoader" blocked the passageway for the "Gravel Box" to reach the door. The intermediate checking steps ("Storage Map" and "Pass Map") are shown in Fig. 13. No route can be found from "Gravel Box" to "Dest" with cells having a value greater than 7. The grade of delivery convenience is hence 0, meaning the "Gravel Box" could not be delivered to the working spot.

Due to the space conflict, the site superintendent decided to suspend the indoor renovation work for one day (November 17th) and resume it on November 18th after the wheel loader left the site. The site "Pass Map" on November 18th for the "Gravel Boxes" is shown in the top part of Fig. 14. The wide blue area indicates a good accessibility grade. However, the indoor renovation work is already one day behind the schedule.

This situation of delay could be easily avoided by using the MLEM. Had such a spatial conflict been detected early on by the GIS-based MLEM, alternative site layout plans such as the one illustrated in the bottom part of Fig. 14 could have been used. This alternative site layout plan locates the "Gravel Box" and "Misc" to the left of the wheel

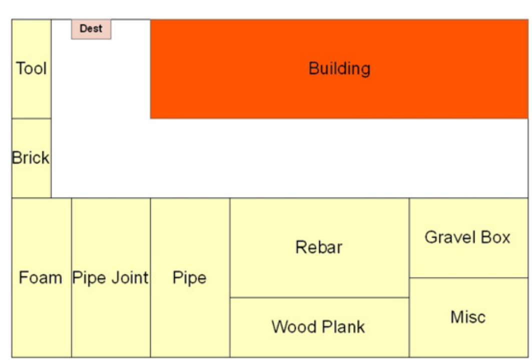

Fig. 10. The site layout map on November 16th, 2010.

Table 1
Attributes of material blocks.

FID	Shape	Name	Unit	cl	st	ut	et
0	Polygon	Foam	Piece	0.9	11/6/2010	12/15/2010	12/20/2010
1	Polygon	Pipe joint	Piece	1.2	11/8/2010	11/20/2010	12/1/2010
2	Polygon	Pipe	Piece	1.5	11/8/2010	11/20/2010	12/1/2010
3	Polygon	Wood plank	Piece	1.2	11/8/2010	12/20/2010	12/23/2010
4	Polygon	Rebar	Bar	1.5	11/9/2010	12/2/2010	12/14/2010
5	Polygon	Misc	Unit	0.9	11/6/2010	12/20/2010	12/23/2010
6	Polygon	Gravel box	Bulk	1.5	11/10/2010	11/15/2010	11/20/2010
7	Polygon	Brick	Unit	0.9	11/12/2010	12/15/2010	12/29/2010
8	Polygon	Tool	Unit	0.9	11/6/2010	11/7/2010	12/23/2010

Fig. 11. A site picture of the outdoor demolition.

loader so that the outdoor renovation work would not block the delivery path and consequently, allows the indoor and outdoor activities to be performed simultaneously without causing any delays.

The weight indices are set to be $\lambda_1 = 1$, $\lambda_2 = 1$, and $\lambda_3 = 2$; and the travel frequency is set to be 1 for all materials. In some cases a small construction site should consider GPC and GDC more than GSP because distance in a small area is not as critical as the pick-up convenience and delivery convenience. This site layout, however, is simple enough to ensure a good GPC and GDC as long as there is no space conflict. GSP thus becomes the most weighted factor. The MAG calculation of the "Gravel Box" for the two cases is illustrated in Table 2.

The MAG of the critical material "Gravel Box" in the alternative plan has a higher value. The GPC (x_1) and GDC (x_2) are all 2, indicating that there is no conflict. The alternative plan has a higher value of GSP (x_3), indicating a shorter path than that of the original plan for the evaluated day. The overall MAG value indicates that the alternative plan provides a better material accessibility. A user can determine not only which plan is more convenient, but also the contributing factor(s). Another important observation is that the alternative plan adjusts the spatial layout to avoid conflicts, but follows construction schedule while the original plan has to extend one day for the work that required "Gravel Box".

6. Discussion

It was noticed during site observation that sometimes a pile of material was used in multiple time periods, i.e., after its *ut*, the material was not used till its *et*. Taking an imaginary situation as an example, material A was stored on site from January 1st. In the following month, they were used from January 8th to 12th. After January 12th, material A still occupied the area, but was not used until February 15th and was used up by February 20th. This material storage and usage needs to be split into two instances: 1, {*st*: Jan/1/2010; *ut*: Jan/8/2010; and *et*: Jan/12/2010}; and 2, {*st*: Feb/12/2010; *ut*: Feb/15/2010; and *et*: Feb/20/2010}. The superintendents or site engineers tend to treat the materials prepared for those two instances as a single pile of material. While the MLEM supports this approach, the user is strongly encouraged to treat material A as two separate material piles to avoid confusion and increase the utilization of the limited site space.

Another issue that warrants discussion is the calculation of the storage dimension for different materials. Presently, MLEM provides information about the material's quantity and type, but leaves the decision on the material storage block to the user. Popescu [31] proposed a general equation to determine the material storage area based on factors such as the maximum estimated quantity in storage space, the quantity of materials can be stored, total quantity of materials required for the project, estimated quantity required per day, average stock time, utilization index for materials, and fluctuation factor. This equation can be incorporated into MLEM as an alternative to assist users in determining the required storage size for different materials.

The current version of the MLEM in this study incorporates the travel frequency as the multiplication factor in the calculation of

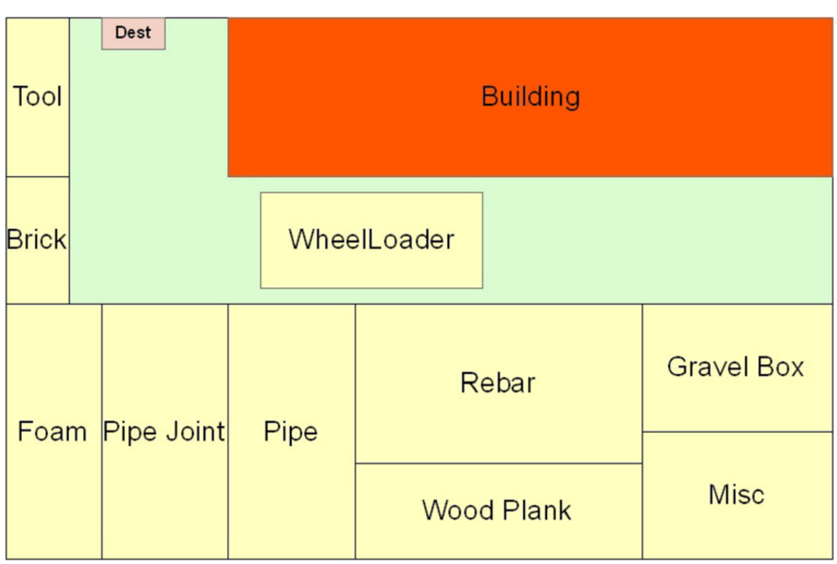

Fig. 12. The updated site layout map with wheel loader.

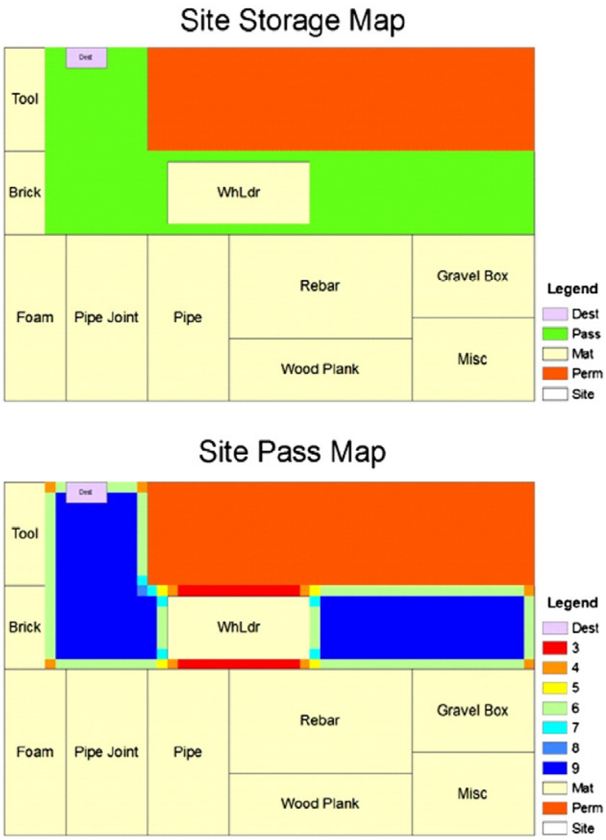

Fig. 13. The site storage map and site pass map.

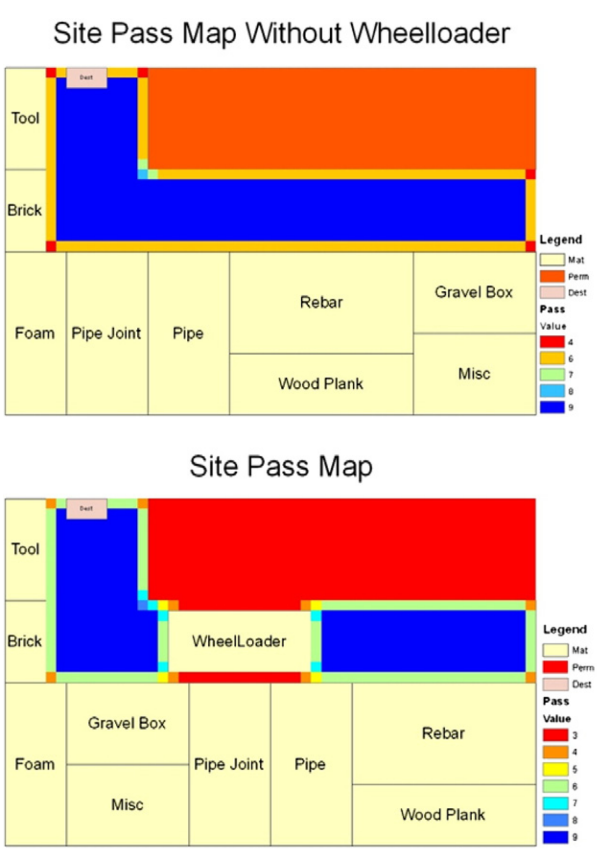

Fig. 14. The comparison of site pass maps.

Table 2
MAG calculation and comparison.

	λ_1	x_1	λ_2	x_2	λ_3	x_3	MAG
Case1: Nov 18th without wheel loader	1	2	1	2	2	1.24	6.49
Case2: Nov 17th alternative plan	1	2	1	2	2	1.42	6.85

MAG. The user can modify its value to match the travel frequency associated with the delivery of a particular material. Researchers such as Cheng and Yang [29] have proposed to calculate the travel frequency by dividing the material demand by the transport capacity. While this method could be incorporated into the MLEM to further automate the site layout planning task, the user must be cautioned of several concerns. Unlike large-scale construction projects that use cranes and trucks with fixed transport capacities for onsite material delivery, building renovation projects mostly rely on labours for manual onsite material delivery, of which the transport capacity varies. Moreover, certain materials are simply not "dividable." For instance, pipe elements with different shapes and lengths are usually quantified by meters in the schedule, but by pieces on site. The calculation of the travel frequency for these materials cannot be totally automated. User involvement and engineering judgment are required.

The main limitation of this research at this moment is the lack of an optimization component. Due to the fast pace of materials arriving and consumed on site in renovation projects, this optimization must consider not only spatial layout, but also time schedule. A best plan designed spatially for a day may cause conflicts in other days. Under this constraint, an ideal optimizer shall be able to process temporal and spatial information in an integrated manner. The prototype presented in this paper is a decision-support tool that provides a mechanism to automatically evaluate given material layout plans based on a quantitative measure of the material accessibility. While this quantitative measure is being used to compare alternate material layout plans, it might not be appropriate to serve as the single optimization objective. Thus, the system developed in this study shall be used as an evaluation tool, not an optimization tool. They system does overcome this shortcoming to a certain extent given its capability of advising users on potential alternative material locations to avoid the space conflicts. Those locations could be obtained from the Path Map (Fig. 4) of the entire site. Cells with a value of 9 could all serve as alternative areas for temporary storage as long as they do not cause conflicts for other materials. For example, the user will be suggested of all the available spaces located to the right of the wheel loader for the "Gravel Box" and advised to move the material before November 17th to avoid conflicts in the case study. However, the user must make their own decision on how to relocate the materials. The system will check the newly generated plans to determine whether conflicts still exist.

7. Summary and conclusions

This paper presents a material layout evaluation model, MLEM, for building renovation projects. The newly developed MLEM was based on the MAG, a quantitative measure of the material accessibility that was redefined in this study as the synergy of material pick-up convenience, delivery convenience, and delivery distance. Algorithms and tools were developed and implemented on a GIS platform to automate the tasks of reading user inputs; generating lists of material demand and material supply; calculating the grades for pick-up convenience (GPC), delivery convenience (GDC), and the shortest path (GSP); and calculating the overall MAGs for site layout plans. The resulting system had a set of default values for model parameters to minimize the efforts required in the model development. These values could be modified to suit the varying needs of different projects and thus, the resulting system was flexible and extendable. The dynamic nature of a renovation project and its site was captured by linking the construction schedule to the material demand, and linking the material schedule to the material supply. The system adopted a two-step approach. The first step aimed at detecting space conflicts and generating conflict-free plans. The second step calculated MAGs for all conflict-free plans, forming the base for plan comparison and selection.

The resulting system was tested and validated in an on-campus building renovation projects. It was concluded that the quantitative measure of MAG was comprehensive by considering all three critical factors in onsite material delivery; e.g. pick-up, delivery path, and delivery distance; for individual materials on a daily basis. As an element level planning tool, MLEM captured more details to better suit the needs of building renovation projects than the existing area level planning models. The MAG evaluation parameters were flexible and highly customizable. The concepts of and the calculation methods for those parameters were tied to the working experience and knowledge of field crews (e.g. comfortable working range and the maximum GPC ratio). Combined with the friendly user interface that was designed with the inputs from field crews, the MLEM was readily adoptable by the industry. As a part of our future work, the MLEM will be expanded to include an optimization module and applied in an upcoming garage repair project on campus.

The developed GIS-based MLEM proved GIS to be a powerful tool for evaluating renovation project site layouts. It provided a programmable environment to develop a quick and intuitive communicating interface, and greatly automated the process of reading user input and data analysis. Its spatial operation and analytical capabilities facilitated the quantification of critical factors. The built-in database system was able to manage information-rich construction materials and facilities, and more importantly, improve construction planning efficiency by integrating geometric, location, and thematic information in a single environment.

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