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Automated System for Multi-Objective Optimization of Construction Supply and Site Logistics

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Abstract: Planning construction logistics involves the retrieval of significant amount of project's spatial, temporal, and supply data that are used to generate efficient logistics plans. This paper presents the development of an Automated Multi-objective Construction Logistics Optimization System named "AMCLOS". The main objective of the system is to support construction planners in optimally planning material procurement and storage with unique modeling capabilities for congested construction sites. To this end, AMCLOS is designed and implemented to provide a number of new and unique capabilities, including: (1) automated detection and retrieval of exterior and interior spatial data of the construction site from already available design electronic documents, such as Building Information Models (BIM); (2) fast and easy input of construction schedule data by reading available schedule data from commercially available project planning software packages; (3) seamless integration of project data that facilitates the definition of various types of spatio-temporal linking and storing all input data in a relational database; (4) utilizing multi-objective optimization and computational algorithms in order to simultaneously minimize total logistics planning and project schedule criticality; and (5) interactive data input and reporting of generated optimization results.

1 Introduction

Construction logistics is a multidisciplinary process that involves suppliers and constructors in the efforts of supplying, storing, and installing material in construction projects. Logistics management is viewed as the operational aspect of Supply-Chain Management (SCM), where extensive effort is made to plan and coordinate the material supply processes at each stage of the project (Sobotka et al., 2005). A research study estimates that improving construction logistics practices can lead to 10% - 30% of cost savings due to decreased probability of material shortages and reduced indirect costs of material handling and transport (SFA/CPA 2005, BRE 2003). Logistics management in construction, however, has an added complexity because of the need to simultaneously consider the site logistics beside supply logistics (Agapiou et al. 1998). Supply logistics focuses on material supply timing and sizing decisions, while site logistics involves material onsite storage and handling efforts. Logistics management requires the integration of data and decisions of material supply and site storage as these two processes are interdependent. For example, deciding on a material delivery timing and size cannot be done without the consideration of both construction progress and site space availability. The required holistic approach of logistics management becomes more complex with the dynamic environment of construction sites.

Previous studies on construction logistics range from qualitative studies of best practices and experience to quantitative models of planning and optimizations. Qualitative studies of construction logistics include the satisfaction of project managers in construction logistics (Jang et al. 2003), effective tools and

approaches for the coordination between site and supply logistics (Guffond and Leconte 2000), role of logistics management in lean construction (Salagnac and Yacine 1999), and best practices of construction logistics management and improvement (Silva and Cardoso 1999). Quantitative studies include stochastic modeling of construction supply process (Caron et al. 1998), the development of performance measurement framework for the evaluation and monitoring of construction logistics improvement (Wegelius-Lehtonen 2001), optimization of construction logistics planning (Said and El-Rayes 2010), and simulation of construction logistics organizational structures and networks (Voigtmann 2010). Investigation of previous research reveals that little attention was given to the development of automated systems that would facilitate seamless integration of diverse and sizable amount of data that is needed for construction logistics analysis and planning. Absence of such systems forms remarkable challenges in applying logistics management practices because of the commitment required to integrate and compile the project data related to construction methods, site space, and material supply.

This paper presents the development a new automated multi-objective construction logistics optimization system (AMCLOS) that is designed to help construction managers in efficiently analyzing, planning, and generating detailed logistics plans. As shown in Figure 1, AMCLOS is a prototype system that was implemented in Microsoft Visual Studio C++ programming Environment, which includes four main modules: construction logistics planning (CLP) module, input data retrieval (IDR) module, data warehousing and processing (DWP) module, and user interface and output (UIO) module. The following sections describe each of these four modules and conclude with the limitations of current prototype and suggestions for future research.

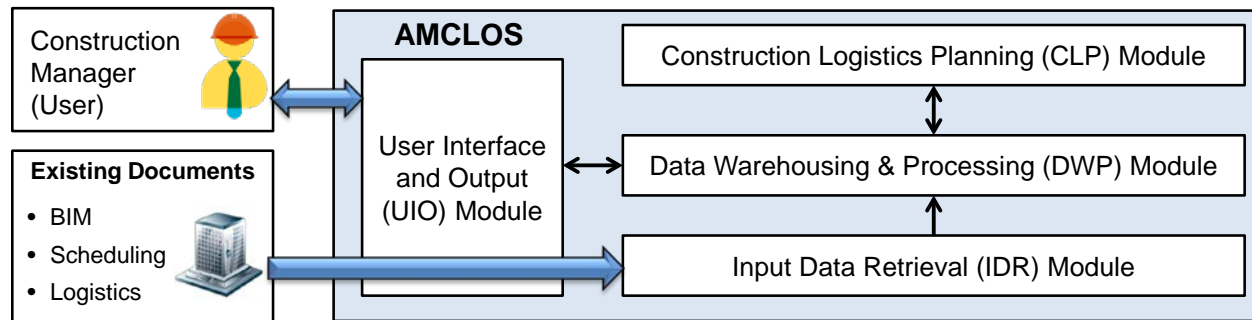


Figure 1: AMCLOS Components

2 Construction Logistics Planning (CLP) Module

CLP module optimizes construction logistics planning by generating optimal material supply and site storage layout decisions to minimize logistics costs and possible increases in project schedule criticality. CLP module is developed using Genetic Algorithms (GA) modeling tool that was applied previously in similar non-linear and complex optimization problems (Deb et al. 2000). As shown in Figure 2, CLP module operates in two possible cases of construction projects: spacious site and congested site. The major difference between these two cases is that spacious sites provide sufficient exterior space that is enough to accommodate site temporary facilities and storage areas at any point of the construction timeline. On the other hand, a clear example of the case of congested construction sites is a building project in a heavily populated or urbanized area, such as downtown zones. Logistics planning in congested construction sites requires additional analysis to enable the utilization of interior building space while minimizing possible scheduling changes for indoor construction activities (Elbeltagi et al. 2004). Such additional analysis of interior space and schedule change requires additional computational efforts, which might not be needed in the case of spacious sites. Accordingly, AMCLOS system assigns the responsibility to the user (project manager) of selecting the case of site space availability based on

his/her individual expertise and preference. The following subsections briefly outline the decision variables and optimization objectives for both cases of construction sites.

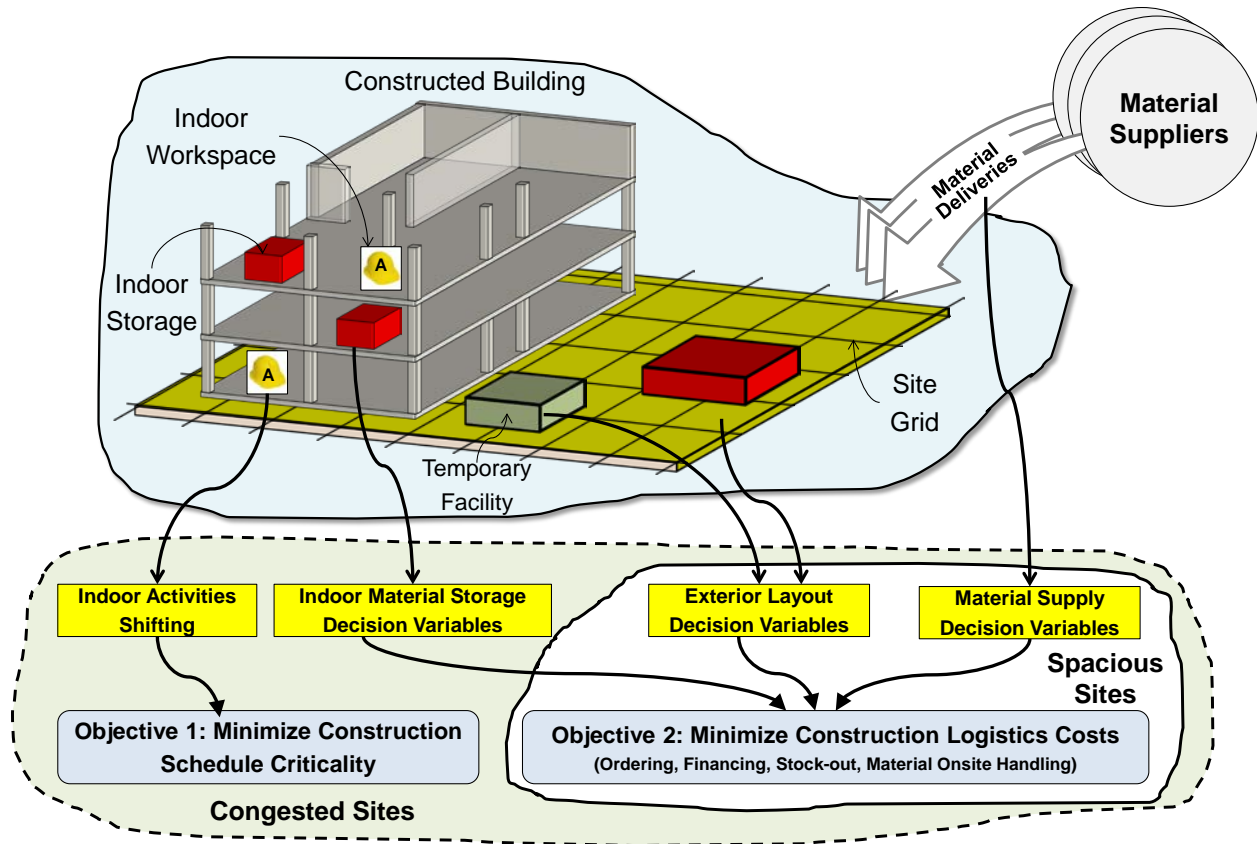


Figure 2: Construction Logistics Optimization in CLP Module

2.1 Spacious Sites Logistics Planning

Logistics planning in spacious sites is accomplished by generating optimal dynamic material supply and exterior site layout decisions that result in minimizing total logistics cost, as shown in Figure 2. The project duration is divided into its major stages that are marked by schedule milestones, where the logistics plan of every stage is controlled by two main categories of decision variables. The first category of decision variables covers exterior site layout of both construction temporary facilities (e.g. site trailer, batch plants, fabrication areas) and material storage areas. Two layout decision variables are considered for each temporary facility or material storage in each construction stage (Said and El-Rayes 2010): 1) its location on a site grid that transforms the continuous exterior space into a set of discrete locations; and 2) its orientation as either 0 or 90 degrees. The location and orientation of facilities and storage areas are constrained by the infeasibility of facilities physical overlapping and placement of facilities beyond the site boundary lines. In addition, exterior layout decision variables are checked against a set of distance and zoning constraints defined by AMCLOS user to represent any operational or safety requirements (El-Rayes and Said 2009). The second decision variables category includes the Fixed-Ordering-Period (FOP) of every material in every stage that is used to calculate the size and timing of material deliveries (Magad and Amos 1995). The value of FOP for each material can range from 1 day, which represents a Just-in-Time (JIT) material, to an arbitrary value that is defined by the construction manager. Supply decision variables are constrained by the maximum delivery size that can be secured from the supplier in

a single delivery. It should be noted that supply and layout decision variables are strongly interdependent. For example, the dimensions of the storage areas are determined based on the material FOP and its calculated delivery size through the utilization of material footprint schedules that are known from previous experiences (Said and El-Rayes 2010). On the other hand, scarcity of exterior space may constrain material FOP in the range of smaller values (e.g. JIT) that results in frequent small material deliveries.

Optimal decision variables of spacious sites logistics planning are generated to minimize total logistics cost that includes ordering, financing, stock-out and layout cost (Said and El-Rayes 2010). First, ordering cost includes purchasing and transport cost of material deliveries that solely depends on supply decisions (FOP) and resulting delivery sizes. Order cost decreases with larger FOP values (large quantity of individual deliveries) because of the application of supplier's discounts of large quantities and better utilization of truck's full capacity. Second, financing cost is calculated as the incurred interest of contractor's capital trapped in the material inventory stored onsite. Financing cost is minimized with the reduction of onsite inventory, which implies considering smaller FOP values or Just-in-Time (JIT) approach. Third, stock-out cost is used to quantify the implications of potential delays of material deliveries using Monte-Carlo Simulation that considers statistical modeling of previous supplier deliveries, project schedule, and contractual liquidated damages. Stock-out cost tends to decrease with larger FOP values that result in fewer material deliveries and less probability of material-related project delays. Fourth, layout cost includes expenses of onsite resources (labor, staff, equipment) during their travel between temporary facilities or resources committed to material handling from storage areas to activities demand locations. Layout cost is mainly controlled by exterior layout decision variables that can be minimized by located site facility and storage areas in close vicinity.

2.2 Congested Sites Logistics Planning

Logistics planning in congested construction sites includes the same decision variables and objective of spacious sites case in addition to other decision variables related to interior space utilization and the objective of minimizing schedule criticality, as shown in Figure 2. Two additional groups of decision variables are modeled in the case of congested sites: indoor activities shifting and indoor material storage (Said and El-Rayes 2012). First, CLP module considers the possibility of shifting non-critical indoor activities with their float periods to clear sufficient space for material storage over extended period of times. The proposed system is limited to the consideration of non-critical activities on the assumption that project duration is fixed and cannot be delayed. Second, indoor material storage decision variables are generated for each material in every stage, which include: 1) indoor storage priority decision that identifies the urgency of indoor storage of this material's deliveries over the other deliveries, and 2) a binary storage type variables that controls if the material is stored outdoor (external layout decisions are considered) or stored indoor (the indoor storage priority decision is considered). If indoor material storage is selected by CLP module, indoor storage priority values are used by a group of computational algorithms to allocate interior building space to the storage of material deliveries in a way that achieves the lowest handling cost and avoidance of interior space conflicts. Indoor material storage decisions are generated considering three possible types of interior space constraints: (1) rooms capacity constraints that limits material storage to the available free space concurrent to other storage areas and activities; (2) rooms availability constraints that limit the storage inside building rooms before their construction time; and (3) permissible storage period constraints that are define by construction planners to limit the material storage during the execution of specific activities (e.g. no cement storage close to painting activity).

The additional optimization objective of minimizing schedule criticality is considered in congested site because of the possibility of shifting non-critical activities. Schedule criticality is quantified as the average of activities criticality, which is calculated as the ratio between the performed activity shift and its total float. Accordingly shifting activities will increase their criticality that will result in increasing the criticality of the whole schedule. It should be noted that CLP module generates optimal activities shifting values in congested sites that balance between two main extreme plans: 1) shifting of all activities to the possible extent to results in sufficient material storage space, lower ordering costs, and higher schedule criticality; and 2) prohibiting activities shifting that results in limited material storage, higher JIT ordering cost, and lower schedule criticality. CLP module utilizes GA's efficient multi-objective optimization approach to

generate optimal values of all interdependent and constrained logistics decision variables (supply and site logistics) that achieve the optimal balance between minimizing both logistics costs and schedule criticality. Accordingly, CLP generates a set of optimal Pareto solutions, which represent different balances between the two logistics planning objectives, where AMCLOS user can select a single solution that fits her/his other planning preferences.

3 Input Data Retrieval (IDR) Module

IDR module is designed to facilitate the automatic retrieval of required spatial, schedule, and logistics data from available documentation of the project and the construction company. As shown previously in CLP module, logistics planning requires wide range of data in order to generate practical and effective plans. Most of these data, however, already exist in distributed documentation files of the project and company's database, such as: 1) project spatial and geometric data that exist in available Building Information Model (BIM) of the project; 2) schedule activities and supplied material data that are defined in the project schedule file produced by available commercial software; and 3) logistics data of material supply and storage that are accumulated over the projects and stored in company's records. The following subsections describe the automated retrieval process for spatial, schedule, and logistics data.

3.1 Spatial Data Retrieval

Project spatial data are retrieved by IDR module from project's BIM file to sufficiently define the geometry of the site and constructed buildings. Building information models (BIM) are virtual rich repositories of projects multidisciplinary data that provide effective tools for communication and sharing of data between project stakeholders and team members (Eastman et al. 2008). It is, however, challenging and time consuming for the project planner to manually obtain spatial data from the BIM file for the purpose of logistics planning, especially for large projects. Accordingly, project spatial data are retrieved from the project's IFC (International Foundation Classes) file that is exported from available BIM-based building drafting software (e.g. AutoCAD Revit). The parsing and analysis of IFC file is implemented using an open source dynamic-link library, named IFCEngine.dll (TNO 2009) that is integrated in the system to enable identifying the geometric attributes of the construction site and buildings under construction. As such, IDR module is designed to retrieve five main spatial attributes from the BIM file, as shown in Figure 3:

- 1) ***The coordinates of the building footprint that is necessary for exterior site layout planning.*** Building footprint coordinates are identified by locating all *IfcSpace* entities (i.e. building rooms) and all building elements (i.e. *IfcSlab*, *IfcColumn*, *IfcRoof*, etc.) and calculating the coordinate of surrounding bounding box of all elements. IFC files don't directly provide the coordinates of a building, which enforced IDR module implementation to indirectly identify building coordinates as the bounding box surrounding all the elements that belong to the building. This is done by identifying the vertices of each building space and room using the functions of the utilized IFCEngine tool that depends on Microsoft Direct X 9.0 graphics programming interface, as shown in Figure 3. It should be noted that the geometry of the site, buildings, space and building elements are modeled in the proposed system as 3D boxes in order to reduce the computational requirements of logistics planning;
- 2) **The centroid locations of building rooms that are needed for the calculation of material handling and layout costs.** Centroids of building rooms are calculated as the average of their vertices that were retrieved previously by IFCEngine.
- 3) **The capacities of building rooms that are considered by the CLP module in assigning interior space to material storage.** The capacity of each room to accommodate construction activities and storage is identified as its area value stored in the IFC file. The area value of each room is obtained by locating the corresponding *IFCQuantityArea* entity that is linked to the room

though relationships with IFC entities, namely *IFCRelDefinesByProperties* and *IFCElementQuantity*.

- 4) **The elevations of building floors that affect material handling cost.** First, the building levels (stories) are identified by locating all instances of *IfcBuildingStory* in the model that has a decomposition relationship with the building through *IfcRelDecomposes*. Accordingly, the elevation value is obtained for each floor from the attributes of the corresponding *IfcBuildingStory* instance; and
- 5) **The coordinates of site boundary to be used in exterior site layout constraints.** Site boundary coordinates are identified as the bounding minimum and maximum coordinates of the mesh points that define the site surface in the model. As such, a series of IFC geometric representation entities (i.e. *IfcProductRepresentation*, *IfcReperesentation*, *IfcRepresentationItem*) are located for the project site entity (i.e. *IfcSite*). Accordingly, the coordinates of the mesh points (*IfcCartesianPoint*) of these geometric representations are obtained to generate the site boundary minimum and maximum coordinates.

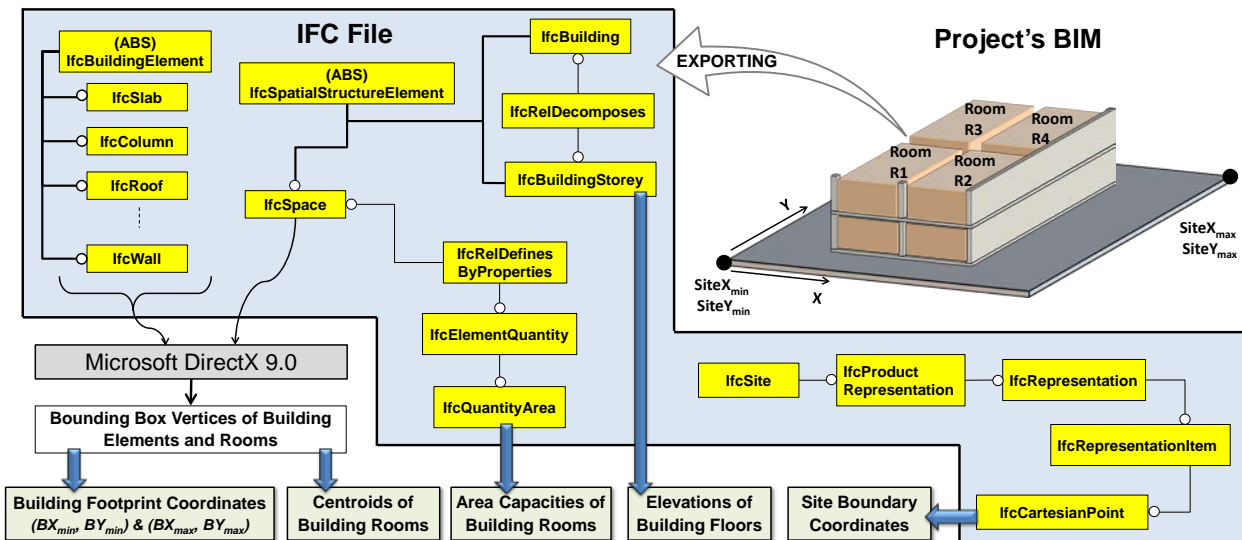


Figure 3: Summarized Flow Chart of Spatial Data Retrieval Process.

3.2 Schedule Data Retrieval

Schedule network data are automatically obtained from existing schedule electronic files that are developed using common commercial planning software. The current version of AMCLOS supports automatic retrieval of project network and resource data from a schedule file in the format of Microsoft Access database (mdb) that is exported from Microsoft Project Planner. IDR Module obtains four main categories of schedule data: 1) activities data that include their identification code, name, duration, early times, late times, total float, and free float for each activity; 2) activities logic and relationships that include the index of predecessor activity, the index of successor activity, the relationship type, and relationship lag; 3) material data that include their indices and names; and 4) material assignments that include the identification code of the assignment activity and the demand quantity.

3.3 Logistics Data Retrieval

IDR module retrieves project logistics data from external database files that include supply, site, and integration data. AMCLOS is supported by a group of Microsoft Access database (mdb) files that are dedicated to the storage of logistics data are typically needed over the projects. These database files are used as an indirect interfacing tool to store and transfer common logistics data between projects. Three main categories of logistics data are retrieved from these external databases:

- 1) **Layout data:** that includes types and dimensions of required site temporary facilities; travel cost rates of resources (equipment, personnel) moving between each pair of site facilities; distance and zone constraints between site facilities, material storage, and the buildings; speeds, hourly cost, and capacity or material handling crews; and material footprint schedules that translate delivery quantity values into storage area dimensions.
- 2) **Supply data:** that includes constraints of delivery quantities, shipping cost of different delivery quantities, and expected delays of material deliveries from each project supplier.
- 3) **Integration data:** that includes workspaces of indoor and outdoor activities; rooms creation activities that mark after their finish the availability of corresponding rooms (interior spaces) for material storage; partitioning activities that refer to interior walls activities and result in discrete material storage in individual rooms; and permissible storage periods that links between material storage areas and their favorable storage period defined by activities start and finish events.

4 Data Warehousing and Processing (DWP) Module

DWP module store, organizes, integrates, and process all input data of project logistics planning that are obtained through either the user interface of data retrieval modules. As shown in Figure 4, data warehousing in DWP module includes five main categories of database tables: (1) schedule data tables that store the information of activities, their relationships, construction materials, and their assignments to activities; (2) BIM data tables that geometric information of buildings, floors, building elements, and rooms; (3) supply logistics tables that include material delivery and purchase cost data; (4) site logistics tables that store input data of site temporary facilities, distance constraints, zone constraints, and travel costs rates; and (5) logistics integration tables that include interior workspaces, exterior workspaces, rooms partitioning activities, rooms creation activities, and permissible storage period in interior spaces. Data warehousing also considers dependencies of tables' entries on the elements of other tables, in order to insure the consistency and integrity of the input data (Harrington 2002). For example, AMCLOS user can not define a workspace of an activity in a building room that does not exist in the retrieved building information model.

Some of the input data initially defined by the user are processed and manipulated to generate new data and information that are required for logistics planning and control. Examples of data processing performed by DWP module include: 1) performing the calculations of resource allocation algorithms to generate material demand histograms for every project day that are needed in supply logistics planning; and 2) identify the closest neighboring rooms of every building room, which is considered in the allocation of interior space to material storage areas.

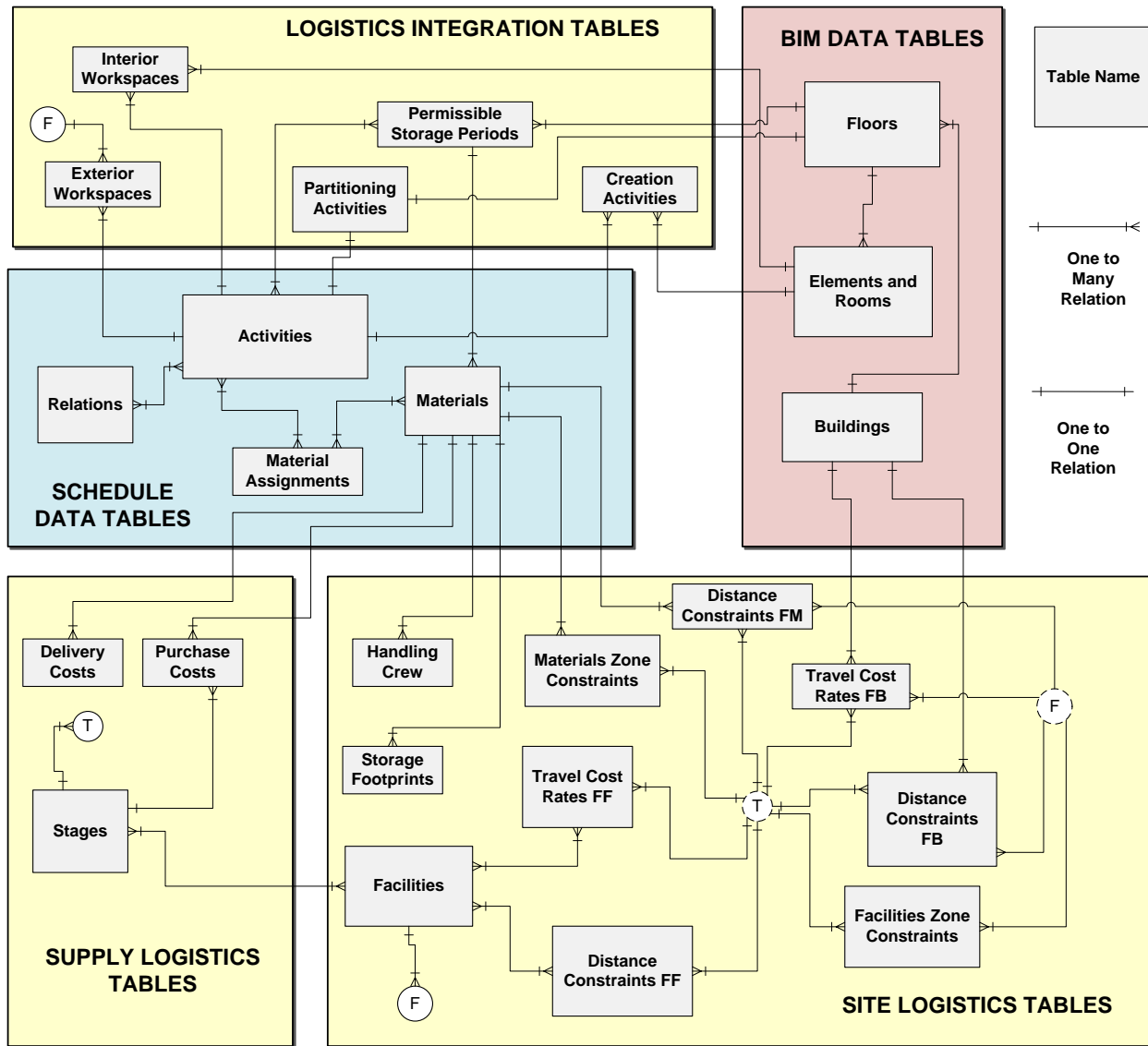


Figure 4: Summarized Entity Relational Diagram of AMCLOS Data Warehousing.

5 Use Interface and Output (UIO) Module

The function of this module is facilitate the interaction with AMCLOS that includes defining and importing input data as well as depicting and exporting generated results. The UIO module guides AMCLOS user in six main steps: 1) create a new logistics planning file or open an existing file saved from previous sessions; 2) input project spatial data by identifying the path to the IFC file and confirming their successful input by showing them on the interface forms; 3) input project schedule data by specifying the location of the project schedule database file; 4) define logistics data through interactive interface tools (buttons, forms, selection tools) or uploading of existing logistics databases to identify logistics supply, site, and integration data; 5) define the GA parameters used in the CLP module to generate optimal logistics plans, such as number of generations and probabilities of genetic operators (crossover and mutation); 6) output the results of CLP module by plotting Pareto optimal solutions, the planning variables of a selected solution, and exporting the results to output spreadsheet files. Figure 5 depicts screenshots of the first input step and the output form showing the Pareto solutions plot of a hypothetical construction project.

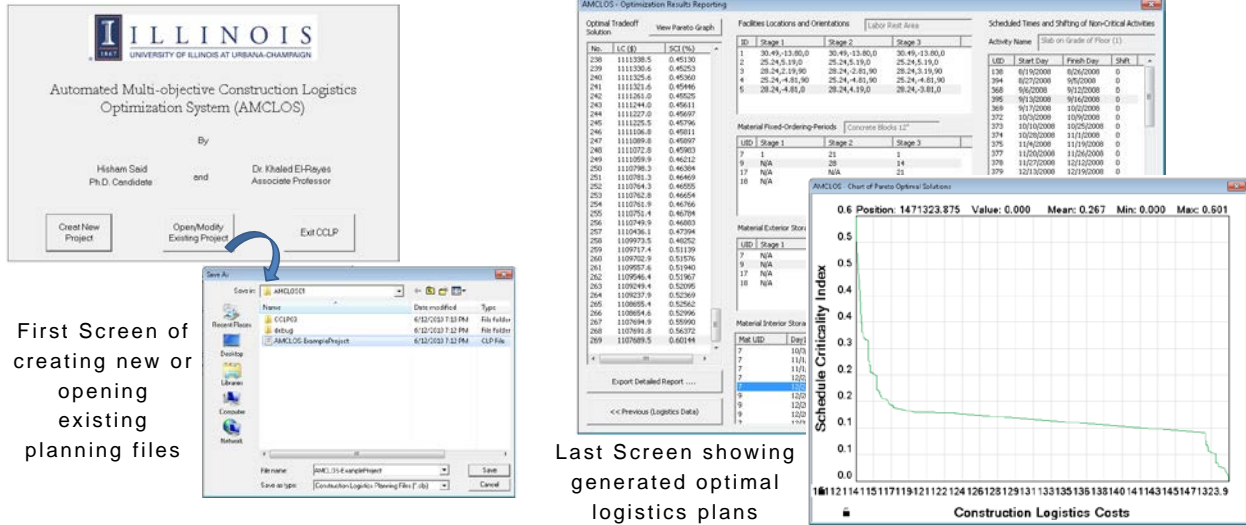


Figure 5: Screenshots of Example AMCLOS User Interface and Output Forms.

6 Summary and Future Work

Construction logistics planning has a great potential of improving project operations and reducing costs by integrating and coordinating the decisions of materials supply and storage from their origin to the installation in the constructed facility. This planning approach is, however, confronted by the challenge of gathering, organizing and integrating logistics data. Accordingly, this paper presents the development of AMCLOS, a new automated system for construction logistics planning and optimization. AMCLOS provides seamless integration of project data and multi-objective optimization of construction logistics for both spacious and congested sites.

There is still a need for further research tasks and study to advance the performance of AMCLOS and overcome its current limitations. Suggested future research work includes:

- 1) Improving geometric modeling of the site, buildings, elements, and facilities by considering irregular shapes that provide more realistic representation of the project;
- 2) Verifying the performance of the proposed system by implementing it on a real-life project and seeking feedback and evaluation from construction professionals and managers; and
- 3) Enhancing the computational performance of the system by facilitating its operation in parallel computing environments;

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