Integrating BIM and GIS to improve the visual monitoring of construction supply chain management

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A B S T R A C T

In recent years, with the increasing level of competition in the global construction market, several research efforts have focused on the application of information technology (IT), as a way to improve the integration process of construction supply chain management (CSCM). Visual representation of the process can provide an effective tool for monitoring resources in the CSCM. In order to support this objective, this paper integrates building information modeling (BIM) and geographic information systems (GIS) into a unique system, which enables keeping track of the supply chain status and provides warning signals to ensure the delivery of materials. First, the proposed methodology is implemented by using BIM due to its capability to accurately provide a detailed takeoff in an early phase of the procurement process. Furthermore, in order to support the wide range of spatial analysis used in the logistics perspective (warehousing and transportation) of the CSCM, GIS is used in the present model. Thus, this paper represents the integrated GIS-BIM model manifesting the flow of materials, availability of resources, and “map” of the respective supply chains visually. A case example is presented to demonstrate the applicability of the developed system.

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1. Introduction

During the last decade, especially in recent years, many researchers have emphasized the benefits of supply chain management philosophy to the construction industry in order to improve the performance of construction and reduce large waste caused by inefficient materials management and control. The need for effective materials management has also been widely recognized throughout the industry community. The PIATech initiative in particular has defined a roadmap for construction in order to advance the development of fully integrated and automated procurement and supply management systems [13]. Although various studies have previously expounded on the importance of understanding the entire scope of the supply chain, it is often associated with the management of the physical distribution of products from raw material through contractor’s supply chain processes to the end product. This perception can be related to traditional contract methods (e.g. design-bid-build), and will vary according to the level of collaboration among the different parties involved in the project, such as Integrated Project Delivery contracts. Assessment of the main collaborative changes from the traditional single-stage procurement towards the adoption of supply chain management in construction reveals further potential for greater collaboration and integration [31]. However, there are limited models that deal with the entire process of construction supply chain management (CSCM), starting with pre-design decisions and their impact on cost and time and ending with monitoring and inspection purposes on construction site.

The term “supply chain” used here to define the stages through which construction resources (material, equipment, personnel) entirely proceed from supply points to the constructions site. Supply chain in construction is more concerned with the planning and directing discrete quantities of materials to the construction site where the object is assembled from incoming materials [27]. A closer look at the construction industry shows that a considerable amount of waste produced is rooted in poor management of the material supply chain (e.g. delivery services, inventory, communications). In this regard, the use of information technology (IT) is suggested to achieve better logistics processes, and avoiding delays [29]. Various IT applications have been used in the literature as a way to improve the integration process of CSCM. These applications have harnessed the capabilities of IT to facilitate the mapping of time and cost resources and also transportation analysis and optimization models to improve logistics performance [22].

Williamson et al. [41] conducted research on the use of information systems within supply chain management and the application of the Internet in the monitoring of deliveries. Tserng et al. [36] developed an information system tool to optimize the inventory cost of the entire supply chain or only one of the supply chain members and also to reduce the integrated inventory of construction materials. Navon and Berkovich [37] developed an automated IT model to improve material...
management and control. The model generates list of materials to order, report the status of materials on site, and alerts when the material quantity on the site is less than the defined minimum. Even though the automated model addressed the major problems of material management, there is significant room for improvement. For example, determining the availability status of materials enables managers to specify resources early in the design process and extends the available lead-time for procurements [26].

The geographic information system (GIS) is another information system technology that has been proposed in the literature. Among them, Cheng and Yang [6] developed GIS-based cost estimates in order to identify options and solutions for problems regarding materials layout. When GIS layout data is linked with three dimensional (3D) site models, the whole material circulation path in the site can be vividly simulated [23]. The substantial input data required in the CSCM is often derived both from automated sources (software applications, bar code readers, sensors, and analytical instruments) and manual interactions [8]. In this regard, an automated system that integrates radio frequency identification (RFID) and global positioning system (GPS) technologies with GIS for tracking resources can eliminate labor-intensive data collection and limitation of distance of line-of-sight [12]. The main purpose of using automated tracking systems in construction is to improve efficiency, reduce data entry errors caused by human transcription, and reduce labor costs [25]. Application of GIS and RFID not only has the advantage of providing automated tracking in a construction site, but also allows real-time transportation information to be compatible with GIS and readily available along the supply chain process. These models require the user to specify and input the material data, however, it was suggested to use information about past transactions is the marketplace [5].

In the traditional way of managing the supply chain, the focus may be on the site activities (e.g. reduce costs or duration of site activities), or on the supply chain itself (e.g. reduce logistics costs, lead time and inventory). The main objective of logistic analysis is to minimize the combination of vehicles, hours, or miles required to deliver the product [39]. It is estimated that transportation costs accounts for 10-20% of construction costs [34]. In addition to the transportation costs, the model developed by Said and El-Rayes [33] is utilized to minimize ordering and financing costs. The traditional approaches to the control of the CSCM are not adequate any more, and we have to clearly show process information for any other section of the supply network (e.g. at the suppliers or sub-suppliers) [1]. Therefore a shift of methods for the integrated management and improvement of the supply chain and the site production is needed [40].

This paper proposes improvements to the current practice by taking advantage of integrating building information modeling (BIM) and GIS into a unique system, which enables keeping track of the supply chain status and provides warning signals to ensure the delivery of materials. While BIM systems concentrate on creating objects with the maximum level of detail in geometry, GIS are applied to analyze the objects, which already exist around us, in most abstract way [4]. BIM is a promising technology that combines the design and visualization capabilities with the rich parametric object and attributes modeling of GIS [19]. To develop a BIM-GIS system, it is important to bring the benefits of both technologies together into a single model, which can maximize both values. A number of studies addressed the application of GIS in BIM environments and building information models in the geospatial domain. For instance, Isikdag et al. [18] investigated the application of BIM (IFC in particular) in a geospatial context in order to transfer the geometric and semantic information of the building elements into the GIS. Choi et al. [7] also established a prototype system to share the building information models among indoor GIS applications. Peña-Mora et al. [30], on the other hand, recognized the need to integrate different IT technologies, such as GIS and digital building information, in one reliable platform for emergency response management. Elbeltagi and Dawood [10] developed a BIM-GIS system for visual monitoring of repetitive construction progress. Irizarry and Karan [17] presented an integrated BIM-GIS system to visualize the 3D model of tower cranes in their optimal locations. This paper, therefore, represents an integrated BIM-GIS model for visualizing the supply chain process and monitoring the flow of materials.

The main focus of this research is on the procurement phase of a project in which information pertaining to the location of supply chain assets is visually monitored. Since the data used in the CSCM can be derived from the design phase of the project, the model starts the tracking process by providing a platform to organize data entry. In addition to avoiding mistakes and errors that occur in data entry, it is helpful to ensure data integrity and consistency across various stages in the CSCM. It should be noted that the results obtained from the model to make design decisions and material selection is not a primary goal of this research. Instead, the use of information defined in this stage and their effect on the supply chain of construction resources is the goal. The literature review described in this section pointed out several studies on the use of IT-based tools for CSCM. In the next section we explain why BIM and GIS are used in the model as IT tools that support supply chain management in construction. In addition, how the integration of BIM and GIS may overcome the shortcomings of the commercially available tools is also addressed. Then, the proposed methodology is described in detail in five different steps. While some steps of the methodology are performed either in BIM or in GIS itself, material and component data is exchanged frequently between these two technologies. Through a case study, the fourth section demonstrates the potential usefulness of the proposed methodology in managing construction supply chain. The authors are well aware of the need for coordination of interorganizations’ decision making to address CSCM improvements [42], however, identifying the organizational approaches to the CSCM is beyond the scope of the current research. Even though the study mainly concentrates on the flow of materials from the suppliers to construction site (i.e. end user), the success of such an effort will address some aspects of lean construction in terms of efficient use of resources and cooperative supply chain management. Lookahead planning, for example, can be effectively accomplished by dividing anticipating assignments based on location or quantity and to attract management attention on what is supposed to happen at some time in the future [3].

2. Role of BIM and GIS in a CSCM Model

To enable complete visualization of the resource flow status, an IT-based model was developed to support decision making during the CSCM process. With the use of IT-based tools such as BIM, supply-network visibility and accurate information concerning the status of material at different stages can be enhanced [43]. As a result, the managers have access to a BIM model with the full range of material information [14]. The proposed model uses BIM capability to accurately provide a detailed takeoff in an early phase of the procurement process and GIS to support the wide range of spatial analysis used in the logistics perspective (warehousing and transportation) of the CSCM. Having a parametric model that includes precise BIM components makes it possible to define discrete quantifiable elements to show detailed material and component properties [20]. These quantities, which are provided by BIM tools, can be exported to a spreadsheet or an external database, and must include the material to be procured, both temporary and permanent [2]. Some issues may arise when an element does not exist in the building model (e.g. scaffolding) or a needed quantity cannot be calculated based on the component properties. Quantities that cannot be extracted from the building information model directly would need to be manually entered. This model, also, takes advantage of the BIM visualization capability to generate reports and alerts graphically. Therefore, the time required to provide a list of all the materials is largely diminished and, instead of using statistics reports, the 3D visualization of the material status is displayed at any specified time by comparing the incoming quantity and the planned quantity to date. Moreover,
existing software tools used in managing supply chain rely on bar charts and histograms to represent data that require further consideration to determine the location of materials in building or through their supply chain. A major improvement occurs with the use of BIM, which provides strong premises to overcome the graphical representation of material status. Many BIM tools provide scheduling functionality and simple functions to link construction schedule to the 3D model, allowing visualization of the sequential construction of the building [9]. When material status cannot be easily seen on a construction site due to physical obstacles, computer-aided visualization is needed to facilitate reporting of process status. The visual report produced by BIM can clearly demonstrate the availability of materials and their final locations, which ultimately facilitate monitoring and properly provide process transparency [32].

To evaluate logistics constraints involved in the material delivery process, GIS is used to map the entire supply chain process, e.g., location of suppliers, transportation, value adding, and nonvalue adding activities. In this sense, the GIS module of the system uses descriptive information (e.g. transportation network) and geographical location of suppliers in order to provide an ideal solution to manage costs of transportation [21]. The GIS maps are depicted using value stream mapping symbols in order to clearly show who plays what role in the supply chain and where and how a feature moves/changes over a period of time [35]. One advantage of this approach is that it can integrate supply chain systems for warehousing and transportation. As both warehouse and transportation management systems are involved in the supply chain process, they can work together to map the physical flow of goods and to reduce overall costs and lead times along the extended supply chain [24]. When material specifications and properties are identified, there is a need for data exchange standards to make this information readily available and easily accessible [11].

Fig. 1 shows the model framework. The workflow is described as follows: (1) using different types of elements (e.g. walls, columns, doors...), the availability of materials are evaluated in the pre-design phase. (2) Sourcing refers to the process of finding suppliers of goods and the impact of supplier’s location on cost and schedules for a given construction project. (3) Logistics is the management of the flow of materials between the suppliers to the construction site in order to meet the requirements of a given project. Logistics involves the integration of information, transportation, inventory, warehousing, and material handling. (4) Performance Management provides visibility into key performance indicators (KPIs) across the supply chain. And (5) monitoring and inspection deal with available and accurate information concerning the status of material at different stages within the construction supply chain.

The studies carried out on integration of these two information technologies can be categorized into two interrelated levels: the fundamental level and the application level. At the fundamental level, we concentrate our efforts on data exchange standards and interoperability at the data level. At the application level, we focus on the development of new methods for using the full potential of information technologies, each addressing a different part of a problem. This research aims at providing a new tool for managing supply chain at the application level. Enabling interoperability at the semantic level is a key issue for bringing the benefits of both technologies together into a single comprehensive model. There are various information exchange efforts such as the Construction Operations Building information exchange (COBie) and the OmniClass that address how 3D-shape information along with attributes can be used within the AEC industry and GISs. In other examples, buildingSMART International provided Industry Foundation Classes (IFC) as a standard language for exchanging construction data, and the Open Geospatial Consortium (OGC) introduced the Geographic Markup Language (GML) for data interoperability in the geospatial community. The IFC is the only public, nonproprietary and well-developed data model for buildings and architecture that exists today [9]. Although much of the IFC contents are specific to the building, buildingSMART International has been working on extending the scope of IFCs to other civil engineering domains, such as GIS-based systems. In this manner, Industry Foundation Classes for Geographic Information Systems (IFC) has been developed for enabling the exchange of geographic information in GIS with the IFC schema [16]. In order to demonstrate and promote such standards, OGC initiated collaborative efforts (e.g., interoperability program) in the 3D domain, which resulted in many opportunities and discovered issues related to CAD-GIS-BIM architecture [28].

The information exchanges mainly occur through importing or exporting file types in interoperable formats that can be used in other visualization applications. In the proposed model, the latest IFC 2 × 4 release was used as the data repository for addressing the geometry, relations, and attributes. Although it provides the new ability to connect BIM tools to GIS databases, the proposed approach suffers from a lack of interoperability between GIS and BIM. With an IFC file, it is not possible to save multiple georeferenced building models on a server and edit attributes and queries. One alternative for this is to use CityGML as a format of data exchange. However, it cannot be applied for building activities and therefore is not to be used for the proposed application. In this study, some solutions are used to alleviate these limitations. In order to accurately locate the building within GIS context, spatial coordinates is defined and transformed from local coordinate systems to the real word coordinate system (i.e. georeferenced) at the beginning of the process. Then, with the aid of the designed plug-in, geometry, layers, and other properties of the elements in BIM restructured to enhance data exchange between two applications. Without it, despite the fact that entire BIM models can be shown, many of the properties of building elements cannot be supported in GIS. In addition, MS Access is used as a central database where all BIM and GIS data can be exported/imported as 3D objects into the database. In the next section, information flow among the various applications in the BIM-GIS model is presented.

3. BIM-GIS model description

The overview of CSCM information flow among the various applications in the proposed system is shown in Fig. 2. In the following sub-sections, different stages of the model are explained.
3.1. Step 1 — BIM Module: define building elements and properties

The building’s elements are defined at this stage, and the type of each element is determined based on the material being used. The required amount of building information (i.e., 3D geometric representations and related semantic information) is provided as an IFC file. Although the IFC data model is mostly utilized during the design phase of a project (as-designed model), it has the capability of representing the as-built data by assigning as-built information in the meta-data of building information models [15]. Using the IFC specification, we can define an object with different geometries and different contextual information, and assign the meta-data and the as-built model into a separate layer in the IFC file. For instance, Autodesk Revit relates each object type from the building information model to the corresponding IFC entity type (e.g., IfcCurtainWall, IfcDoor, IfcMaterial). When exporting a model to IFC format, it can be saved and edited as an external text file, and using IFC property sets, we can add simple meta-data to an IFC file. The IfcPropertySet defines a particular type of object, and the object type (IfcTypeObject) is used to define the common properties of a certain type of an object.

In order to have the right resources in the right quantities (at the right place) at the right moment while minimizing costs and rewarding all parties involved in managing logistics, supply chain information systems require a great deal of data input. These inputs play an essential role in managing logistics functions such as storage, transport, distribution, delivery, and package tracking. All data entry and manipulations are done by means of the interface developed in the BIM software application. By comparing each data entry with the required information for its corresponding supply chain, the model is able to check and verify data inputs for completeness, consistency, and integrity. In addition, in the proposed system, each piece of data is entered only once and mainly in the BIM module. Depending on the type of building materials, the

Fig. 2. Information flow in the supply chain model.
supply chain process could be engineered-to-order (ETO), made-to-order (MTO), assembled-to-order (ATO), and made-to-stock (MTS) products. Because each of these four general types of construction products has its own supply chain, defining object classes (or object family) may be appropriate to address how they are structured and how they are edited. Then, relevant parameters should be defined for each object class in order to define the properties of building elements in BIM model. For example, manufacturer parameter could be applied to find the location of suppliers.

Characteristics described by Elfving [28] and Arbulu et al. [16] can be used as a basis for defining properties and parameters for different types of products. ETO products are specially made based on either fully designs or only details received from an engineering company (e.g., power distribution equipment, preassembled rebar components). They are defined by parameters such as manufacturer, model, raw materials, and drawings. MTO products are usually products manufactured once customer orders have been placed (e.g., cast-in-place concrete, prefabricated panels). Usually, MTO products are characterized by manufacturer, model, and raw materials parameters. ATO products are also assembled (manufactured) after customer orders, however these products are usually standard or made of standard components (e.g., doors, windows). In BIM module, manufacturer and model parameters have been used for ATO products. Finally, MTS products are commodities (e.g. consumables such as bolts) characterized by short lead times. Even though manufacturer is the only parameter that used for MTS products, they should be defined as a resource for the corresponding activities in the schedule in order to address how often they are ordered and in what batch size.

3.2. Step 2 — BIM-GIS Module: develop visual model representing the availability of materials

This step involves identification of all available resources defined earlier in the BIM model and recognition of their relative distance to the construction site. Since building elements in BIM identify what needs to be purchased, it is possible to extract all information directly from the BIM tool. 1st pricing plug-ins is a good example of a BIM application that takes advantage of this capability. This application provides real-time quotes on doors and windows from different databases across the Internet. Autodesk Seek is another system that enables designers to discover, preview, and download BIM models, drawings, and specifications from U.S. manufacturers. However, given the complexity, the diversity of the supply chains and the number of variables in relation to the logistic costs, there is a need for more powerful technology. Considering the large amount of spatial data used in the C SCM, GIS could be of great value to manage logistic perspective of CSCM. Once the availability of resources is developed in separate GIS layers, managers can look to the accessible materials or equipment and use only those resources that are available and meet all schedule constraints for the current project. Following the previous steps, most information like schedule of material delivery, the components of the building and their installation locations, and schedule of their relevant activities are available in GIS database. Each component is annotated with its delivery time and installation/consumption time, thus, storage duration of each component can be calculated in this step. This option is used in the BIM module of the model to calculate order due dates and demand forecasting. While demand forecast is obtained from the construction schedules, it should be borne in mind that date and duration of activities are uncertain due to the existence of various constraints.

3.3. Step 3 — GIS module: total cost analysis

In this step, GIS-based spatial analyses such as network analysis and attribute analyses have been used to provide an optimal solution to manage costs of supply chain logistics. In order to achieve logistics’ aim of reducing costs, while simultaneously adding value to the supply chain process, we can reduce costs due to reduction in inventory costs and aggregate different demands into one pool of storage, or by trade-off between inbound and outbound transportation costs. Movement of materials among different parties is a critical consideration in cost analysis, which is closely related to location, or spatial information of the suppliers. Due to its significant impact on the overall expenditure, cost of transportation is considered as one of the deterministic factors in choosing suppliers. In this essence, the main requirements of GIS module are inventory costs (capital, storage, taxes, insurance and obsolescence), vehicles characteristics (vehicle costs, vehicle capacity, vehicles available, vehicle travel time), average fuel price and product unit. Each vehicle starts from its corresponding supply point, forwards materials to a given customer (e.g. construction site) according to the demand less than the capacity of the vehicle. It is possible to analyze the past transactions in the marketplace to generate a set of optimal tradeoffs between transportation costs, lead-time and material quantity.

With regard to this need, geographic information, quantities and properties of building components included in the BIM model are combined with network analysis in a GIS. With respect to the integration with GIS module, transportation mode(s), warehouse capacity, and product characteristics are utilized to identify optimum transportation cost and the facility that is used to fill the order. Ordering costs depend on the number of material orders and the quantities. In addition, real-time transportation information generated by the GIS module can be compared with the expected (or as-planned) data in order to assess the delivery performance. With the aid of network analysis function in the GIS module, various modes of transportation can be considered. Fig. 3 shows the input variables used in the GIS module to calculate transportation time and cost. To select the alternative with least cost or time of logistics, the associated time and cost should be assigned to each input variable. For example, the quantity of material ordered (i.e. lot size) can affect the associated time or cost of raw material procurement.
and product manufacturing (i.e. input variables 1 and 2 in Fig. 3) and the time the material is stored on the construction site before it is used in production (i.e. buffer size) can change the associated time or cost of installation step (i.e. input variables 6 in Fig. 3). However, the level of details required in the analysis and the sequence of operation will vary depending on the product type. For example, MTS products do not have raw material ordering step or ETO products may need more details regarding to loading and unloading activities.

3.4. Step 4 — GIS Module: Visualize Logistic Pattern

GIS can be applied for logistics management to provide accurate and up-to-date information on the status of materials and resources. GIS need dynamic and instance location information of resources to map the status and issue warning, which enable managers to respond immediately if the resource arrives to the site at the wrong time. There are various identification and storage technologies, such as barcode, RFID, and GPS, all of which have been utilized with GIS in tracking process before. These systems can automatically track real-time data of location and identification of new materials. Difficulties would be expected because the present model did not include a fully automated resource tracking and locating.

When the position of each construction resource is available, GIS can display the current location of a resource and estimate the arriving time to the predetermined construction site. Comparing the estimated times with the planned times, it is possible to provide managers with warning signals that allow them to take timely actions in response to prevent or alleviate any delays and increase delivery reliability.

3.5. Step 5 — BIM module: monitoring and graphical representation of material status

The objective of the BIM monitoring module is to overcome the main challenge in supply chain process of material tracking; to provide the managers with reliable information on material status, whether the inventory is located at the site or elsewhere along the supply chain. The status of material availability is established by tracking the building materials that are identified with corresponding ID in the BIM model and registered into the tracking system. Also, there is a link between these IDs and schedule activities, so the material needed for a given activity along with the time can be determined. When materials arrive at or their delivery date obtained from previous step, the respective material availabilities can be visualized in the BIM model.

The BIM solution can be used for field inspection and quality control of materials, as a last component of supply chain. The quality control (QC) department needs to know the up-to-date status of materials to monitor the status of a work order and to plan ahead. A major portion of quality inspection requires checking the material properties of various products at the construction site, which are available in the BIM model. Therefore, to access material information, we need to bring BIM model to the field. Commercially available system is available to deliver and update BIM information with the use of the hand-held wireless devices or tablet PC software [38]. As a part of quality inspection process at jobsite, each component (e.g. material ID) is scanned (or automatically tracked) by the field personnel, so the updated status can be gathered and updated. The QC management system has three main components, a PDA, tracking device (e.g. barcode scanner, RFID), and a portal. While the BIM database is on the portal side, field personnel can update BIM attributes using the personal digital assistance (PDA) equipped with systems software (e.g. Vela systems). PDAs display the material properties, thus field personnel can check the relevant items with their specifications and enter quality and inspection results into their PDAs. This information will be transferred between the PDA and portal by real-time synchronization, enabling the managers to check the process and monitor inventory status on the BIM model. The material status is created as instance parameters in the BIM model and assigned to all categories like walls, windows, doors, and columns. To demonstrate the use of the proposed steps across the GIS and BIM domains, a case example is presented in the next section.

4. Case study

The aforementioned procedure is employed for monitoring CSCM of a building project in Carrollton, Georgia, “The School of Nursing at the University of West Georgia”. The project involved a three-story, 65,000 square foot building accommodating all functions for nursing education and support spaces. The facility will house a variety of instructional spaces, including a 135-seat auditorium, 65-seat tiered classroom, computer classroom and lab, and flexible classrooms, as well as administrative and faculty support spaces. The project is scheduled for completion in early 2013. In order to support and facilitate interoperability with the GIS application, the BIM model has been developed based on the IFC standard. There are many available commercial BIM software applications (e.g. Autodesk Revit, Archicad, Vico, Bentley Micro station, etc.) that support the IFC standard. In this study, Autodesk Revit Architecture 2012 was used as the BIM software application. However, the methodology on how to visually model the CSCM does not depend on the BIM software application but rather on the way it applies parametric rules associated with the objects in BIM. In this respect, a plug-in interface is embedded in the BIM software tool (i.e. Revit Architecture) to provide improved visual reporting and valuable information on the process of exchanging product model data with GIS. Therefore, it can be applied for software tools that support plug-ins to BIM platforms (e.g. Bentley systems, Rhino). Furthermore, an overview of BIM tools or features of those tools intended to fulfill model applications is briefly introduced.

Fig. 4 shows a designed Revit plug-in interface, on which 3D model view of the building is shown in the BIM environment. Autodesk Revit has a.NET framework application-programming interface (API), which makes it possible to use any of the .NET compliant programming languages (C#, VB.NET, F#, etc.) to develop a plug-in. The plug-in has been developed in C# with the .NET Framework 3.5. First, BIM models of building elements need to be defined according to the element class or family and product specifications. Revit provides the capability to create multiple object catalogs that enables users to provide 3D electronic catalogs of products in BIM. In addition, one can take advantage of available data from building product manufacturers or online databases (e.g. Autodesk Seek, Buildsite, etc.). Based on the type of supply chain, the building elements are categorized into ETO, MTO, ATO and MTS products. This categorization addresses how relevant parameters should be defined for each object class in order to track the supply chain process. For example, a model of an ETO product should have the main attributes of ETO supply chain such as design information, critical raw materials, and supply chain actors. However, a MTS model requires fewer attributes to visualize the relationships between actors and processes as well as their logical sequence in the process.

After loading the plug-in into Revit, the system asks the user to select a building element in the drawing area. Then, according to predefined characteristics, its related product type (e.g. ETO, MTO, etc.) gets highlighted in the plug-in browser. It should be noted that the highlighted supply chain is based on the product type defined in the BIM models of building elements, however the user is enabled to change the product type, which means that the model considers different supply chain process. Pre-fabricated panels and cast-in-place concrete object classes, for instance, are predefined as “MTO” products that have three parameters (i.e. manufacturer, retailer supplier, and construction site). Selecting an element of those objects classes immediately shows the user the type of element (i.e. MTO) in the dialogue box. Also, the capability of changing the product type allows user to deal with different supply chain process and therefore different numbers of parameters. If the user changes the product type to ATO, only two parameters (i.e. retailer supplier and construction site) are considered by the model. The role of these parameters in determining
the status of materials is described later in the paper. A list of building elements is available to choose from in the plug-in browser menu. The user can access the element's information by selecting the element command button in the plug-in screen or from the main screen. Readily available BIM-based libraries provided by the building product manufacturers will enhance the applicability of the plug-in to real world projects. These BIM models not only enable contractors to easily access the technical information, but also support synchronization of procurement with design and construction in the AEC community.

The BIM module automatically quantifies specific materials as soon as they are modeled into Revit and then exports the properties for objects selected by the user to a central database (e.g. MS Access). The same approach can be used in the different BIM platforms. For the purpose of this study, one material is considered for each type of product. The schedule date (e.g. installation/consumption date) was extracted from the construction schedule, while detailed information about materials (e.g. size, weight) was obtained directly from the BIM model. As previously mentioned, BIM's database characteristics provides the ability to extract quantities in different forms. The descriptive attributes of the four types of products are shown in Table 1. It is noted that there are several suppliers for every item. For example, 72 different suppliers are attached to the metal panel item, including four different types according to the “metal application”; (1) preformed (prefinished) walls, (2) insulated metal panels, (3) composite metal panels, and (4) cladding panels.

In the second step, all descriptive and geographical information in the central database are exported to the GIS module of the system in order to map the availability of resources. The location of each supplier and the construction site are represented as a set of 2D points having x and y coordinates. The geographic distribution of resources is analyzed by means of spatial statistical methods. In this case, GIS measures the degree to which suppliers are concentrated or dispersed around the construction site (or project location). From the GIS module, distribution of metal panel suppliers can be measured by means of geographic standard deviation, which is calculated using Eq. (1):

\[
\sigma_{\text{Geo}} = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \bar{x})^2 + \sum_{j=1}^{N} (y_j - \bar{y})^2}{N}}
\]

Fig. 4. 3D building model of case study and user interface of BIM model.

Table 1
Descriptive attributes for each type of products selected from the case study.

<table>
<thead>
<tr>
<th>Item Type</th>
<th>Element Name</th>
<th>Grand Total</th>
<th>Total Area (SF)</th>
<th>Unit Size (ft)</th>
<th>Unit weight (lb)</th>
<th>Design duration</th>
<th>Installation date</th>
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<tbody>
<tr>
<td>ETO</td>
<td>curtain wall</td>
<td>690</td>
<td>10,956</td>
<td>2.35 x 6.45 x 0.52</td>
<td>231</td>
<td>45 days</td>
<td>02/05/2013</td>
</tr>
<tr>
<td>MTO</td>
<td>metal panel</td>
<td>49</td>
<td>477</td>
<td>8.31 x 1.28 x 0.08</td>
<td>8.2</td>
<td>–</td>
<td>10/18/2012</td>
</tr>
<tr>
<td>ATO</td>
<td>glass window</td>
<td>211</td>
<td>1849</td>
<td>4.64 x 1.8 x 0.56</td>
<td>68</td>
<td>–</td>
<td>09/15/2012</td>
</tr>
<tr>
<td>MTS</td>
<td>brick veneer</td>
<td>88,313</td>
<td>20,524</td>
<td>0.83 x 0.28 x 0.23</td>
<td>0.92</td>
<td>–</td>
<td>5/10/2012</td>
</tr>
</tbody>
</table>
Where \( x_i \) and \( y_i \) are 2D coordinates of supplier locations, \( X \) and \( Y \) are 2D coordinates of project location, and \( N \) is the number of suppliers.

A directional distribution of insulated metal panel's suppliers is shown in Fig. 5 (ellipse shape). To compare distributions of different types of panels, new maps containing a circle centered on project location with a radius equal to the standard deviation of suppliers around project location are created in GIS. Fig. 5 shows how dispersed are the suppliers with a radius equal to the standard deviation of suppliers around project types of panels, new maps containing a circle centered on project location shown in Fig. 5 (ellipse shape). To compare distributions of different 2D coordinates of project location, and \( N \) is the number of suppliers. Therefore, the availability of resources that satisfies the user constraints can be developed in separate GIS layers. The most common constraint to find suppliers is to limit the distance to the construction site. Fig. 5 (upper right) shows the suppliers located within 100, 200, and 500 mile of the construction site. The distance can be measured using two main methods: (1) straight-line distance from each cell to the source (i.e. construction site), and (2) travel distance through a given route (i.e. transportation network). Also, one can find the suppliers that are located within an area such as Georgia (bottom right). Because each point is annotated with its installation or consumption time, managers can look to the GIS material layers and use only those alternatives that meet all time and location constraints for the current project. One of the benefits of the proposed approach is that the distribution of suppliers can be measured by weight value that has been used to determine the Regional Priority credits of the LEED rating system. In the case study, this concept of credit is used to address geographically specific environmental priorities for supplier locations. Although the user can get distances on available web mapping applications such as Google Maps, there are many limitations in terms of operations and transformations that justify the utilization of GIS. First, GIS can handle large amounts of data simultaneously, however, limited number of data can proceed on Google Maps. In addition, Google Maps/Earth lacks spatial analysis and data transforming functionality at their current state. The suppliers are chosen, and the geographical information as well as logistic details for those being extracted to manage costs of supply chain logistics.

In the third step, GIS helps to provide an optimal solution that minimizes the logistics costs, which combines the cost of orders, warehousing and transportation. Total cost of logistics (TC) is calculated as described in Eq. (2):

\[
TC = (\text{Cost of Order}) + (\text{Inventory Cost}) + (\text{Vehicle Cost}) + (\text{Fuel Price Cost})
\]

In Eq. (2), cost of order is a cost for each order placed that can be fixed or dependent on the number of units ordered. In order to minimize this component, we need to order materials together (i.e. at once). Inventory cost is the holding costs per item per unit time, that is, this component is a function of the order quantity and the period of time between delivery and installation of an item. Ordering and delivering materials as late as possible could be useful because of their low order quantity and minimal holding time. However, there will be an increase in order cost due to increased number of orders. Table 2 summarizes each of these cost elements for different types of product selected from the case study. The data for logistics costs were obtained from the contractor annual Reports, cost center reports, and financial team of the project suppliers. For example, the contractor estimated expenses for management and overhead cost of orders based on its previous records, and represents this item as the number of orders. They are specified as percentages of total material cost, to aid the comparison process. The in-formation regarding the quantities and scheduling of the selected materials for the project is also shown in Table 2. Knowing the delivery time of each order, it is possible to calculate the inventory cost.

Transportation cost can be represented along with the vehicle cost and the fuel price cost. These components are dependent on the type and number of trucks, the travel distance between suppliers and construction site, and material properties (i.e. size and weight). In order to demonstrate the model’s capabilities, five different types of trucks (as listed in Table 3) are taken into account when identifying the required number of trucks. A gross vehicle weight (GVW) is the maximum weight value of a vehicle, including the total of the weights of a vehicle and cargo and a payload is defined as the total weight of all cargo that a vehicle carries. Also, the size of the loads for trucks is limited to \( 53 \times 13.5 \times 8.5 \text{ ft} \ (L \times H \times W) \). Using the properties identified above and quantity of material for a given order, the required

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**Fig. 5.** GIS maps representing the availability of materials.
number of trucks can be determined. Then, fuel price cost is calculated according to the distance traveled per unit of fuel used by trucks in miles per gallon (MPG).

Considering the large amount of descriptive and geographic data involved, there is a great potential to use GIS in construction project supply chain logistics. The application of GIS to this step primarily seeks to explore the optimal way to transport materials from a given supplier to the construction site (i.e. number and time of orders, order quantity, and transportation methods) and the associated cost of transportation. The model utilizes the network analyst extension of ArcGIS to find the shortest path, travel distance and travel time. Determining the optimal number of orders, along with the order quantity and time is accomplished using the python language module available in ArcGIS. This is an efficient method of executing iterative processes with the aid of the spatial operation of ArcGIS (e.g. network analysis), allowing us to create and automate GIS workflows quickly and easily. For the four selected materials, the number of alternatives to be examined can be up to 203. To manage the process effectively, it should start with the least number of orders (i.e. one order) at the latest possible time (to reduce inventory cost). Then the order and inventory costs are calculated for each alternative (i.e. different time and quantity of order) until the total cost increases the preceding total cost. The whole process is repeated for the next order, and the optimal fleet of vehicles is determined. The total cost of each material is obtained by adding transportation costs to order and inventory costs. The results of this analysis showing the optimal number of orders, time and quantity for each of them, and type and number of trucks corresponding to the least transportation cost for a given order are presented in Table 4.

Using a barcode label, which is obtained from the building information model, all the documents and packages corresponding to each component are identified. The data related to the arrival of materials and their dispatch is exchanged between the engineering company,

Table 2
four main elements of logistics costs.

<table>
<thead>
<tr>
<th>Item type</th>
<th>Element name</th>
<th>Grand total</th>
<th>Order cost</th>
<th>Inventory cost</th>
<th>Vehicle cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETO</td>
<td>curtain wall</td>
<td>690</td>
<td>1.41 × OCi</td>
<td>3.0E − 05 × Qi × Ti</td>
<td>0.01 × (15 + 2.25(2 + Hr)) × Ti</td>
</tr>
<tr>
<td>MTO</td>
<td>metal panel</td>
<td>49</td>
<td>0.54 × OCi</td>
<td>1.6E − 03 × Qi × Ti</td>
<td>(9.3 + 1.4(2 + Hr)) × Ti</td>
</tr>
<tr>
<td>ATO</td>
<td>glass window</td>
<td>211</td>
<td>0.91 × OCi</td>
<td>7.6E − 04 × Qi × Ti</td>
<td>(7.9 + 1.2(2 + Hr)) × Ti</td>
</tr>
<tr>
<td>MTS</td>
<td>brick veneer</td>
<td>88,313</td>
<td>0.049 × OCi</td>
<td>4.0E − 07 × Qi × Ti</td>
<td>0.01 × (40 + 6.2(2 + Hr)) × Ti</td>
</tr>
</tbody>
</table>

OCi= Number of Orders, Qi = Quantity for the ith Order, Ti= Period of Days between Material Delivery and Installation, Hr= Travel Hours between Supplier and Construction Site, and Tr= Number of Trucks.

Table 3
Descriptive attributes for each type of trucks selected for the case study.

<table>
<thead>
<tr>
<th>Truck Type</th>
<th>GVW (lb)</th>
<th>Payload (lb)</th>
<th>Fuel Consumption (MPG)</th>
<th>MPG for empty truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36,300</td>
<td>25,300</td>
<td>−0.0246 W + 6.63</td>
<td>6.62</td>
</tr>
<tr>
<td>2</td>
<td>56,000</td>
<td>41,050</td>
<td>−0.0246 W + 6.286</td>
<td>6.28</td>
</tr>
<tr>
<td>3</td>
<td>60,600</td>
<td>40,800</td>
<td>−0.0258 W + 6.285</td>
<td>6.26</td>
</tr>
<tr>
<td>4</td>
<td>80,000</td>
<td>55,750</td>
<td>−0.0235 W + 6.205</td>
<td>6.18</td>
</tr>
<tr>
<td>5</td>
<td>92,000</td>
<td>66,200</td>
<td>−0.0263 W + 5.883</td>
<td>5.86</td>
</tr>
</tbody>
</table>

W = Total Weight of Load (1000xlb).

Fig. 6 shows one example of the analysis result of the GIS for “Brick Veneer” material (as a MTS product). The model starts the process by one order and is followed by the identification of the optimal quantity and time for the order to achieve minimum logistics cost. The process is repeated for the next number of orders (i.e. 2, 3, and 4) until the total cost increases the preceding one (i.e. four orders). As can be seen, as the number of orders increases, the cost of order and inventory decreases while the transportation cost (i.e. vehicle and fuel cost) increases. Increasing the number of orders can make a substantial decrease in inventory costs due to the smaller quantities of materials in the shorter duration of storage; however, it increases the transportation costs. As shown in Fig. 6, the total logistics cost is minimal (i.e. 4.61% of the total material cost) for the three orders.

Once all the supply chain data have been available, the last step of the GIS model involved visual demonstration of the logistic process. The visualization process is based on the information regarding material quantities, delivery scheduling, and the major player (e.g. suppliers, customer, owner, etc) executing logistic processes and activities, which are already in the database of the model. The GIS maps of work sequence logistics are depicted using value stream mapping symbols. The technique is used to map material and information flow required to bring a material to the construction site and summarizing them visually. The value stream for “curtain wall” was mapped at two different phases consecutively: (1) engineering design process, which involves detail design, sending detailing for approval, and receiving approval, and (2) manufacturing and installation, triggered when physical materials and work flows existed. This sequence is based on the supply chain category that has been defined previously as ETO in the first step of the BIM model. The supply chain process, typically, contains the following steps: an engineering company provides the detail design; the owner checks the detailed design; if design is accepted, the supplier can start manufacturing the product; the manufacturing phase, as shown in Fig. 7, contains two sub-phases: pressing and painting, assembling and glazing; followed by transportation, inspection, unloading on construction site and finally installation.

Using a barcode label, which is obtained from the building information model, all the documents and packages corresponding to each component are identified. The data related to the arrival of materials and their dispatch is exchanged between the engineering company,
material suppliers and construction site using the IFC data standard. After creating the IFC model in the BIM environment, the engineering company sends the contents and the tracking data of each object to the material supplier in an IFC file. The material supplier can access any time-based parameters that need to be updated based on the latest status. These tracking data are supposed to be created in the building information model, and shared between the suppliers and construction site personnel. However, they do not need to fully understand the contents of an IFC file, scanning the barcodes shows the parameters that need to be updated through the different phases of the supply chain. Therefore, the updated status of the component can be gathered and returned to the system as well as the GIS database. Because each object in a GIS model has time attributes, it is possible to compare the actual times with the planned times to graphically show the supply chain process through different color schemes. The associated colors are blue, green, yellow, and red, for delivered, in-time (no delay), pending, and late (possible delay) respectively. The mathematical algorithm for displaying the GIS results in a meaningful way is shown in Fig. 8. This algorithm is described further in a later section. As mentioned earlier, value stream mapping symbols are used in GIS software (i.e. ArcGIS) to display map labels. Furthermore, some mapping and visualizations functions available within GIS can help to adjust the formatting of map labels. The GIS software allows mathematical scripting (either JavaScript or VBScript) to be used for comparing time data (i.e. actual and planned times) and changing the appearance of map labels. Unlike the BIM module that changes the color of objects, different labels (labels with same shape but different colors) are used in the GIS module. The main advantage of this method is its simplicity, which will assist in understanding the entirety of the transformation of demands into finished goods. Fig. 7 shows an example of how the value stream for the “curtain wall” is mapped in the GIS with symbols and numbers. As determined in the previous step, curtain walls should be ordered two times; 43% (i.e. 300 pieces) in the 3rd month and 57% (i.e. 390 pieces) in the 8th month of the project. The red color for the “truck shipment” of the first order indicates that the activity has a possibility of causing the delay, while the green color for the preceding activities (e.g. manufacturing facility 1 and 2) means that they have no delay (in-time). As expected, all symbols for the second order are shown in yellow (i.e. pending).

Using the same information utilized in the logistics monitoring, the status of material within the supply chain is visually presented in the building information model. Again, from the type of supply chain defined earlier in the first step of the model, there are different parameters for each object class. Starting with the most number of parameters (i.e. raw material supplier, manufacturer, retailer supplier, and construction site) we have ETO, followed by MTO, ATO, and then MTS products with only one parameter (i.e. construction site). All these parameters are defined as a Date-Time variable and have two entries; one for schedule and one for actual date. The user should enter all schedule entries either manually or by using a direct link to the project schedule. On the other hand, actual entries are updated based on the element’s latest status. Each element is identified and tracked using barcode assigned to the corresponding ID in the building information model. A web-based file-hosting portal was used for sharing information throughout the supply chain. Once the element passed through the different phases of the supply chain (e.g. manufacturing), the actor (e.g. manufacturer) must update the actual date accordingly so that the data can be easily imported into the building information model. In the case study, however, data were stored on the web-based portal manually. Following this, the actual
dates were compared with the schedule dates in order to alter an elements’ appearance. How the visibility of objects change depends on the criteria being used to categorize elements and how many elements share the selected criteria. For this project, the aforementioned color codes (blue, green, yellow, and red) were used to alert the user of the delivery of materials. For the purpose of programming this procedure, a status determination algorithm was developed on a mathematical basis (Fig. 8).

As shown in Fig. 8, there are four possible states regarding the status of “Actual Date” (AD) and “Schedule Date” (SD). As mentioned earlier,
ETO products have four parameters, therefore their highest value of i is four (i.e. i ≤ 4). Using the same reasoning, only one parameter (i.e. i ≤ 1) is considered for MTS products, which helps to know when the MTS materials are delivered to the construction site. When there are no actual dates among parameters, the model considers the parameter as “null”. Therefore, the fifth schedule date (SD5) for ETO product is considered as “null”. Furthermore, the “Pending” situation, which is coded with yellow, only occurs when there are no actual dates (AD) at all. In the absence of actual dates, the model gets the user system date as the current date and compares the current date (i.e. today) with the schedule date. All the monitoring process is done by means of the plug-in interface embedded in the BIM software tool. In addition to the actions related to data manipulation, another function of the BIM plug-in interface is to facilitate the presentation of the flow of building elements in a supply chain. Although it is possible to present the status regarding all the building elements, generally it is best to limit the number of elements selected (i.e. filtering) in order to concentrate on specific building elements or the ones with the greatest potential to cause delay.

There are two ways by which a user can view the material status in the BIM environment. The first is to select a given material (e.g. curtain wall) or materials, and then generate a color-coded view of material status. The second approach, which is shown in Fig. 9, is to select a status (e.g. late) and then filter the materials. In this approach, we only consider those elements that satisfy the status criteria as presented in Fig. 8. When the user selects any number of elements, the count of selected elements, along with the key properties, is displayed for the user. Filtering the elements allows users to further refine the materials they want to consider. For instance, the user can limit the selection to the late delivery of materials and then focus on just the “Curtain Wall” category. With the type of status selected by the user, “Curtain Walls” that satisfy the status criteria will appear with the color that have been assigned to the respective status. It is possible for the user to change the default colors from the visibility and graphics dialog box. Fig. 9 shows an example of how the status of the “curtain wall” is visualized in the BIM environment. The red color indicates that those “curtain walls” have a possibility of causing the delay, while the yellow color for the other elements means that no actual dates are provided for those “curtain walls”. Also, for the purpose of simplicity, the parameters entities are enlarged in the current view. As Can be seen, the entity for “retailer supplier-actual” date is empty (null), and because the current date (i.e. 06/03/2012) value is greater than the “retailer supplier-schedule” date, the status color is returned as “red”. This capability provides managers with reliable information on material status. As it is represented, the result is shown for curtain walls. But, the proposed system is not limited to the extents of exterior elements and interior visualizations can be created as well. The view functionality in many BIM software applications allows the user to zoom in/out the selected elements as well as control other visualization features. We only need to select an interior element; the same procedure will be followed for the chosen elements.

As the last component of the CSCM, BIM can be used to assist the inspection process to the field. The first quality inspection is performed at the time of delivering the materials to the construction site. The inspector should check products to ensure that they are consistent with the quantities and specifications defined in the BIM. This can be done using the commercially available hand-held devices or tablet PC software. By scanning the barcodes, the updated status of materials is transferred to the file-hosting portal. All information is further used to visualize the material status for managers. The main difference between the visual monitoring process in GIS and in BIM is that GIS maps represent the status of materials through the supply chain, while the BIM interface helps to easily identify where these materials are used.

5. Limitations of system

Despite the fact that the integration of BIM and GIS provides an effective tool for visual monitoring of CSCM, there are some limitations in their application. In this paper, resource tracking and locating of
material data are performed manually or using barcode scanners, both of which require manual work. Our research objective of monitoring supply chain during the preconstruction stage required us to utilize as-designed data, however, a possible way to represent and integrate as-built information into the BIM model is to add the metadata and the as-built data to IFC-based products. Also, the method proposed for minimizing the total cost of supply chain logistics only works when data for logistics costs are available. The contractor annual Reports along with cost center reports are used for the case study. Nevertheless, that information might not always be available. Since the system relies on BIM data (as an input data), many problems may arise when an element does not exist in the building model (e.g. temporary facilities) or a needed quantity cannot be calculated based on the component properties. If data cannot be extracted from the building information model into GIS system, manual entry of the data is needed. Although the results were encouraging for the single case study, additional case studies with similar input attributes would be required to have higher accuracy.

The BIM part of the system has a plug-in interface that facilitates interaction with the model’s component and sharing of data with the external environment, on the other hand, improvements are needed to facilitate the linkage of BIM and GIS through a common interface. This will have the potential to solve limitations in data integration and software interoperability, and hence, in transferring data between BIM and GIS. Moreover, the proposed system suffers from a lack of interoperability across the GIS and BIM domains. Although, exchanging and sharing data between BIM and GIS tools is facilitated by the use of commercially available BIM and GIS software applications, these tools still require the user to have knowledge about both systems and their functionalities. For example, after importing an IFC file to GIS, the user needs to know how BIM information is represented in the GIS model. In order to propose a solution, a central database (e.g. MS Access) is used for transferring attribute data between BIM and GIS. However, this approach is inefficient and lacks semantic interoperability. In order to fully integrate the GIS and BIM, future work should focus on providing interoperability at the semantic level.

6. Conclusion
An integrated BIM-GIS system for visualizing the supply chain process and the actual status of materials through the supply chain is presented in this paper. First, the building’s elements are modeled in the BIM process, and based on the type of supply chain, each element is categorized into ETO, MTO, ATO and MTS products. This categorization dictates how to define relevant parameters for each object class in order to visualize the relationships between actors and processes as well as their logical sequence in the supply chain process. The benefit of supply chain management practices to the construction industry is receiving the attention of many researchers and practitioners over the last decade. Although various IT applications exist for managing the flow of materials and information from suppliers to end users, models focusing on the entire sequence of the supply chain are limited. These studies either focused on improving the logistics perspective (warehousing and transportation) of the CSCM or dealt with the supply chain visibility and information concerning the status of material. The BIM model takes advantage of available data from building product manufacturers or online databases. This capability will become even more useful in the future, as product manufacturers provide BIM models of their products for the users. Additionally, in the near future, manufacturers will be providing BIM models with their specifications included in the metadata, thus, making it possible to include as-built information in the metadata of the models.

In this paper, a case study is presented in order to illustrate how to approach integrated CSCM. The goal is to enhance the awareness of CSCM by taking advantage of the data richness and visualization capabilities of BIM and GIS in a single system. All data entry and manipulation is done by means of the developed plug-in interface embedded in the BIM software tool (i.e. Revit Architecture). Apart from the building data defined in the BIM model, spatial information (or geographical information), which is used in the transportation and logistics of the CSCM, should be considered as well. In this sense, GIS helps to map the entire supply chain process and to provide an optimal solution to manage costs of supply chain logistics. After identifying the availability of materials in the form of maps, GIS is used to provide an optimal solution that minimizes the logistics costs, which combines the cost of orders, warehousing and transportation. In order to clearly show the sequence of actions in the supply chain, the GIS maps are depicted using value stream mapping symbols.

Another significant outcome achieved by integrating GIS and BIM is that the updated status of the materials within the supply chain can be vividly demonstrated in the model. Because each object has time parameters, it is possible to compare the actual times with the planned times to provide managers with warning signals through different color schemes. This method also enables managers to easily identify what are the root causes of delayed materials delivery and where these materials are used. All the steps explained above were used through a case study. In order to demonstrate the model’s capabilities, four different types of products with their real properties were considered.

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References