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A GRAPH APPROACH FOR THE INTEGRATED SCHEDULING OF GLOBAL SUPPLY CHAINS

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ABSTRACT

The integrated scheduling of production processes and intermodal transport operations along global supply chains combines machine shifts and flexible land transport schemes with overseas transport running a given timetable. This paper proposes a heuristic scheduling method based on the construction of a cost-weighted graph for each shipment, containing only feasible paths regarding time and capacity. In this way, the scheduling task is formulated as a shortest path problem which can be solved in polynomial time by well-known algorithms. The proposed approach can also solve larger problem instances, as demonstrated by means of a test case scenario using real world data.

Keywords: graph model, discrete simulation event, integrated scheduling

1 INTRODUCTION

The integrated scheduling of production and intermodal transport operations in global supply chain challenges both practitioners and researchers. Models to better understand and evaluate this complex problem were developed and studied, yet a sufficiently comprehensive and adaptable one is still missing. This paper contributes to deal with this issue by proposing and demonstrating the applicability of an approach based on a graph model that employs a time function. The approach turns the integrated production and intermodal transport operations scheduling problem into a shortest path (lower cost) problem, which is solvable in polynomial time

The paper is structured as follows. Section 2 presents a review of scheduling and planning methods, shortest path algorithms and graph theory. Section 3 describes a graph model for the integrated scheduling of production processes and transport operations, showing how to convert all the needed data into a time-dependent graph. More specifically, it is shown how to implement simplifications and assumptions to turn real world data regarding the scheduling of production and transport into a graph that leads to a problem that is solvable in polynomial time. In Section 4 a test case scenario employing real world data and statistic results obtained from a discrete event simulation model exemplifies the application of the proposed approach. The scenario comprises an original equipment manufacturer (OEM) located in Brazil, producing goods that have to be transported to an assembler in Germany. Section 5 displays research conclusions and future research topics.

2 SCHEDULING WITH GRAPHS

A brief review of the relevant literature on the subject of scheduling with graphs is presented in this section. The goal of this section is to present the fundaments of graph theory, its uses in contemporary research, and, finally, how it is applied to scheduling problems. Finally, the methods to solve the resulting shortest path problem are described.

2.1 Planning and Scheduling with Graphs

In this field of research, scheduling problems are not new, they have been a subject of interest for the scientific community since mid-1950s (Sewell et al., 2011, Allahverdi et al., 2008). Yet, there has been a growing research interest in scheduling problems, including mostly transport and production planning (Sewell et al., 2011, Graham et al., 1979). In the basic model of scheduling theory it is assumed that the processing time of each activity is constant, although this assumption does not always hold. When considering the possible delays or waiting times, the jobs are known in theory as deteriorating jobs (Jafari and Moslehi, 2011). The majority of literature assumes that setup times are negligible. In practice, however, assumptions with sequence independent setup time are inadequate in modeling any real world problem (Tan et al., 2000).

Authors have proposed models for solving the integrated scheduling problem of a supply chain (Macharis and Bontekoning, 2004, Mula et al., 2010). Nevertheless, most of the models consider a supply chain topology network for production and transport planning oriented to the tactical decision level. The purpose of most of these models is to minimize the total cost of the supply chain (Mula et al., 2010). The demand level, production capacity, and the costs of production, transport and inventory are normally chosen as shared information. Furthermore, other findings stand out (Mula et al., 2010, Macharis and Bontekoning, 2004): (i) one must not contemplate integrated suppliers within the supply chain as most considered supply chain structures are made up of production and distribution centres; (ii) almost all types of intermodal problems are covered by the theory (iii) a large variety of OR techniques have been applied, although most used programs are mixed linear optimal programming with heuristic and metaheuristic models; (iv) new techniques have been developed, but there is still potential for better techniques.

2.2 Solving the Shortest Path Problem

In graph theory, the shortest path problem is the question of finding a path between two vertices (or nodes) in a graph such that the sum of the weights of its constituent edges is minimized (Christofides, 1975).

The shortest path problem plays an important role in the combinatorial optimization because of its fundamental characteristics and wide range of application, the problem has been studied in both theoretic and algorithm aspects (Zhang and Lin, 2003). There are several algorithms developed with the objective to solve this problem, probably the most famous is the Dijkstra's algorithm (Dijkstra, 1959), other relevant algorithms are the Bellman-Ford algorithm (Sampels, 2004) and the Gabow's algorithm (Nepomnyashchaya, 1998). Recent publications on the topic focus on the improvement of consolidated methods.

The graph theory has been the subject of study in a broader variety of fields, although its use to deal with integrated scheduling problems still lacks more attention. Furthermore, many algorithms have been implemented to solve the shortest path problem. In the following section, an algorithm developed by Kennington and Helgason(1980) will be used for solving the shortest path problem derived from the integrated scheduling of production processes and intermodal transport along a global supply chain.

3 GRAPH MODEL

The main idea of the proposed method is to reformulate the scheduling task as a shortest path problem. In order to do this, a graph $G=(E,V)$ is built, carrying all necessary information only on its set of edges E and nodes V. The following section presents the model assumptions, graph construction and the heuristic scheduling scheme.

3.1 Model Assumptions

The model combines a production system, composed of several levels of production, with land and maritime transport. The land transport via trucks is assumed as being flexibly available at any time, whereas the maritime transport is running a given timetable. The model includes one source (e.g. Original equipment manufacturer - OEM) that provides goods to be transported to destinations (e.g. assembling companies ordering goods from the OEM) via several nodes (e. g. ports).

The production system has $l \in L$ levels of production, with machines $m_l \in M \subset L$. After each l level of production there is an $v \in V$ inventory level $v \in V$, which will be used in case of all machines in the next level are occupied, or there are no routes available in the transport system. Each machine m_l has a cost c_m and a capacity k_m, also each inventory level v has a cost c_v and a capacity k_v. Each machine starts processing at the time t_{mx} and finishes at the time $\overset{mx\}}{t_{¿}}$, the time between x and x is the machine processing time. The inventory level also has an initial time t_{v1} and a final time t_{v2}. All this information will be assigned to the edges of the graph in Section 3.2.

The information that characterizes a transport device $s \in S$ is its initial location p_{1s} and destination p_{2s} at times t_{1s} and t_{2s} as well as its cost C_s and capacity k_s. Again, all this information will be assigned to the edges of the graph in paragraph 3.2. Furthermore, the ports $i \in I$ are characterized by their location p_i as well as the cost c_s and the capacity k_s (Mates et al., 2013). All this information will be assigned to the edges of the graph in the paragraph 3.2. Furthermore, the ports $i \in I$ are characterized by their location p_i as well as the cost c_i and the time b_i that apply for transferring orders from one vessel to another.

An order $j \in J$ features a required amount k * and a due date d_j for its delivery to the destination. It is assumed that all orders to be scheduled are available for shipment at time d * at the location of the OEM. Note that for all orders k * and d * are the same.

As the time table for maritime transport is pre-set, there might be waiting times between two subsequent vessels, requiring storage of the cargo and causing additional costs. Given several orders of the assembler, a solution to the scheduling problem is an assignment of all ordered goods to transport devices at specified points in time so that the total cost is minimized. Additionally, the solution needs to respect the available capacity of the vessels as well as the due dates of the orders.

3.2 Graph Construction

In order to get a formulation of the scheduling task as a shortest path problem all the information mentioned in Section 3.1 has to be transformed into a graph representation. Most intuitively, the nodes *V* may represent the production levels and the ports, distributed in the x-/y-plane according to their geographical position, linked by the edges *E* standing for the transport device assigned with the travel time, cost and capacity (Mates et al., 2013). This approach would lead to a constrained shortest path problem which is NP-complete (Handler and Zang, 1980), so it would not be suitable for larger problem instances. In order to overcome this drawback, the graph is built in another way as described below.

The relevant information for a machine m_l was indicated as its times (shifts) t_{mx} and $\overset{mx\}}{t_{¿}}$, cost C_m and capacity k_m. The locations and times can now be stored in two nodes where cost and capacity will be allocated as parameters of the edge between those nodes, as illustrated in Figure 2. The figure shows four machines in two shifts, for instance the m11 line represents the process that occur in the machine m_{11}, been c_{11} and k_{11} the cost and capacity of this machine process, t_1 the beginning time of the shift and t_2 the final time of the shift. The cost and capacity of the machine m_{11} are parameters of the edge, while the beginning and end time are determined by the position of the edge. Analogously the variables c_{21} and k_{21} are the cost and capacity of the machine m_{21} and are inserted as parameters of its edge, the position of the edge indicates the beginning time t_3 and the final time t_4. The same applies for the machines m_{12} and m_{22}, with the variables $c_{12}, k_{12}, c_{22} \wedge k_{22}$, as well as the times.

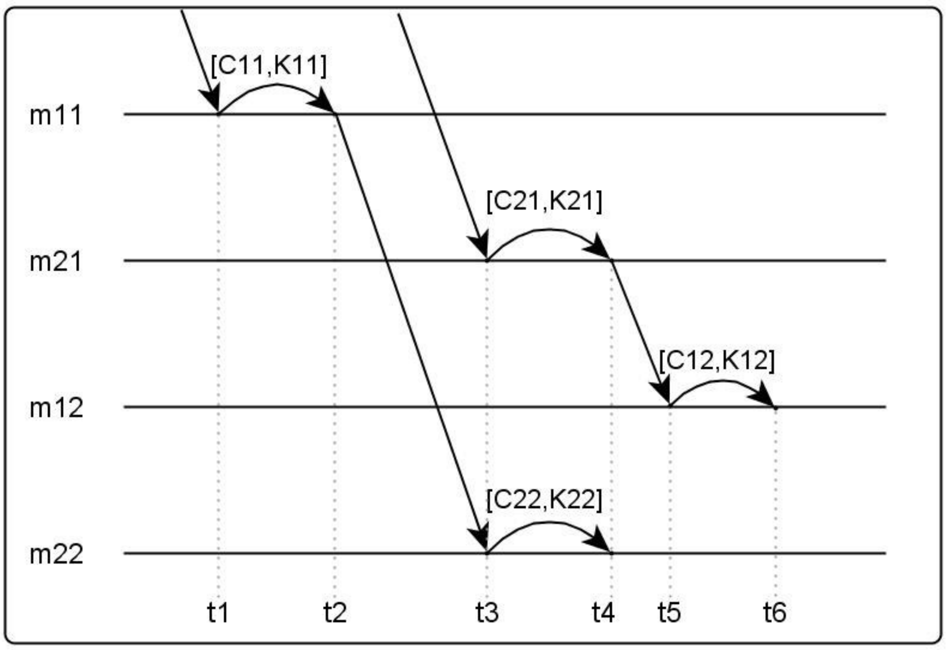

Figure 2 - Turning machine information to edges

The relevant information for an inventory v was indicated as its cost c_v and capacity k_v, being those variables be inserted as parameters of an edge. The initial time t_{v1} and the final time t_{v2}, indicate the edge positions. The Figure 3 exemplifies this situation.

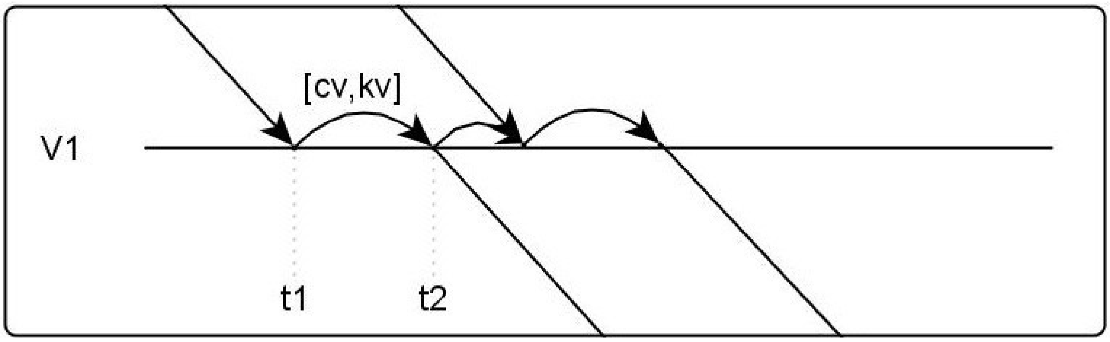

Figure 3 - Turning inventory information to edges

The relevant information for a route segment s was indicated as its locations p_{1s} and p_{2v}, time t_{1s} and t_{2s}, cost c_s and capacity k_s. The locations and times can now be stored in two nodes where cost and capacity will be allocated as parameters of the edge between those nodes, as illustrated in Figure 4. The figure shows a vessel s_1 leaving p_1 at time t_1, and arriving at p_2 at time $t_2=t_1+\Delta t$, where Δt is the expected travelling time of s_1 from p_1 to p_2. Analogically, a vessel s_2 leaves the same port at a later time travelling to port p_3 (Mates et al., 2013).
When a transport device arrives at a port p_i it takes some loading/unloading time l_i until the cargo is ready for the next shipment. This time can also be represented by an edge as shown in Figure 5. All the costs of the operation (e.g. machine and manpower, port taxes, etc.) are associated to the loading edge, which holds the total cost in its parameters. Depending on the schedule of the maritime transport, there might be a time slot between the time where cargo is ready for shipment at some port and the departure times of the next vessels leaving from here. This gap can be filled by considering it as storage, which can again be represented as an edge with the costs and capacity as assigned parameters (Figure 5).

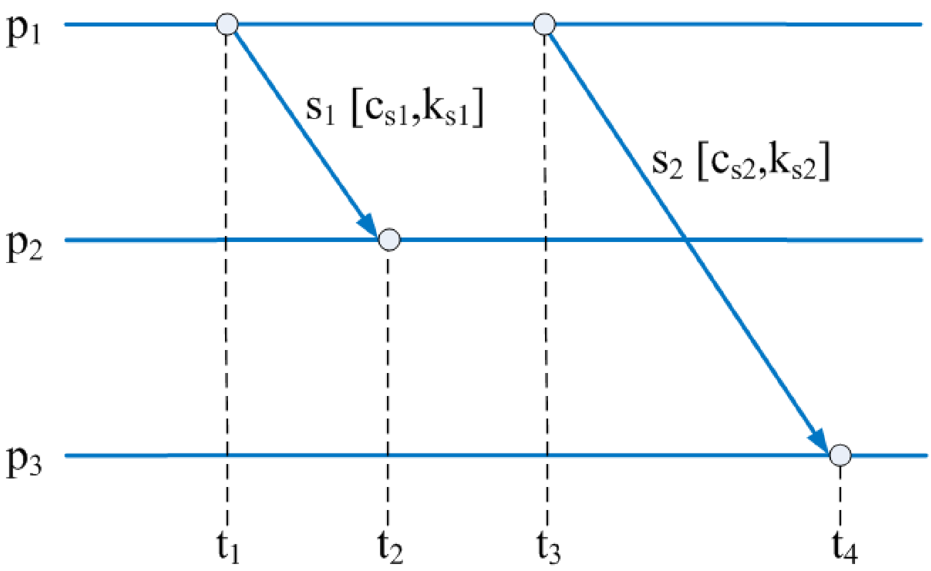

Figure 4 - Turning vessel information to edges

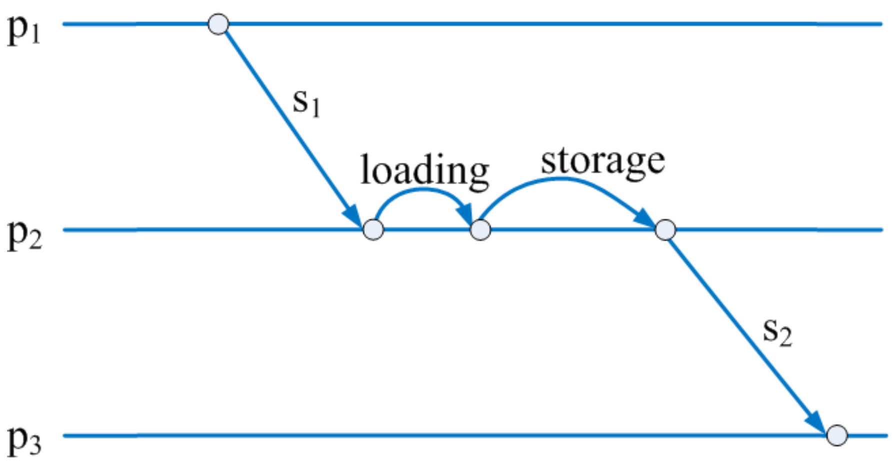

Figure 5 - Connecting subsequent vessels

Based on a schedule for the maritime transport between OEM and assembler, it is now possible to build a graph for each order taking into account the due date τ_j for the delivery. Due to the time-dependency of the graph, only feasible edges *e* representing the production and transport devices m and *s* are included into the graph according to the criterion $t_{2s} < \tau_j$. At this stage, the edges of the graph still have two assigned parameters: cost and capacity. The aim is to formulate the initial problem as a shortest (i.e. cheapest) path problem where edges only carry cost and capacity information. A solution can then be found with one of several algorithms, a few examples are pointed in the Section 2.3.

4 TEST SCENARIO

The test scenario consists of an OEM located in Campinas, Brazil and an assembler in Kassel, Germany. The OEM works with a three level production system, each with three machines as shown in Figure 6. The ordered goods are transported via trucks to the port of Santos. The ports offer maritime transport connections to Rotterdam and Hamburg. The last segment of the intermodal transport is done by trucks that connect the ports with the assembler in Kassel, Germany Figure 7.

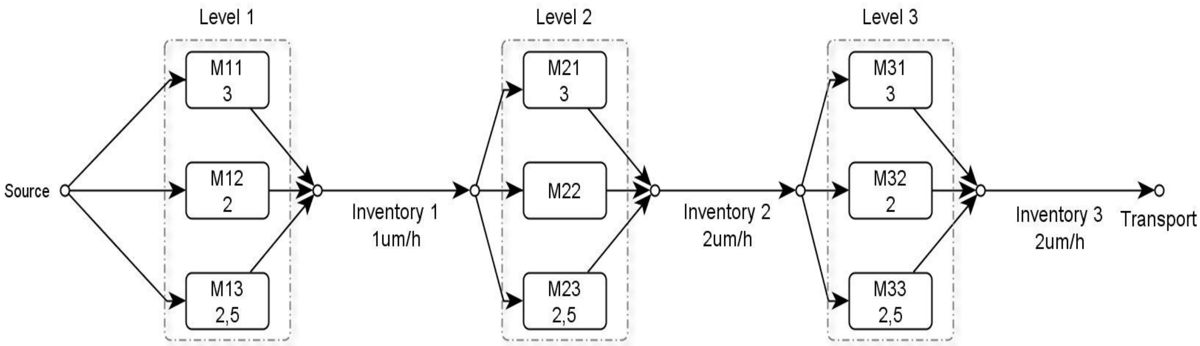

Figure 6 - Production Structure

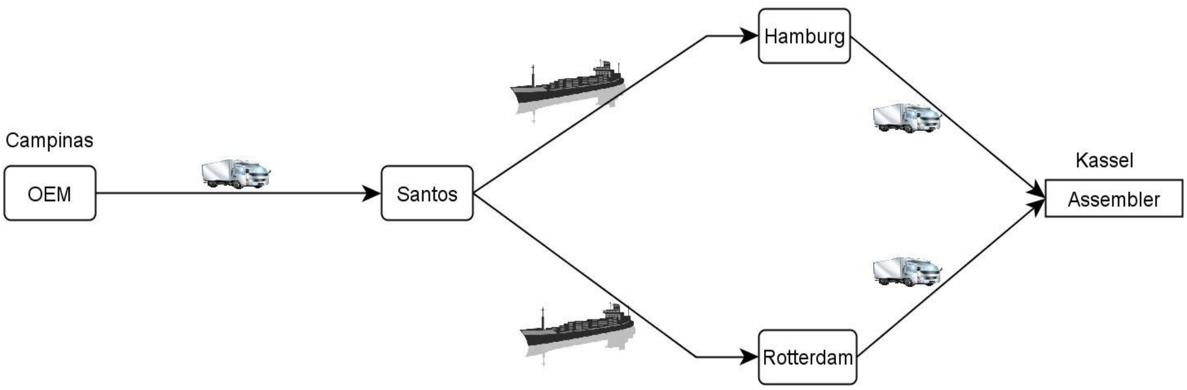

Figure 7 - Transport System

The weekly timetable of the maritime vessels is displayed in Table III, which shows the days of departure and the traveling time. The costs of the vessels are assumed to be all equal.

Table III - Vessel Scales

Origin/Destinations	Time	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Santos/Hamburg	08:00		21			22	28	
	12:00		20	18	31	22		
	18:00			18				
Santos/Rotterdam	08:00			15	19			
	12:00			15		14	25	
	18:00		15		19	19	20	

For this test case the following data, in monetary unit (MU), is assumed: i) Production costs: Machine (1) 300 MU; Machine (2) 200 MU; Machine (3) 250 MU. The cost is the same for all three levels of production; ii) Inventory costs: From level 1 to 2 and level 2 to 3 the cost is 1 MU per shift; from level 3 to the transport system the cost is 2 MU per shift; iii) Transport costs: From Campinas to Santos 10 MU; from Hamburg to Kassel 10 MU; from Rotterdam to Kassel 15 MU; the maritime travels are assumed to cost 50 MU.

The shifts are considered to last one hour each. The costs are all per order, and each machine is capable of producing one unit per shift. In this example the transport capacities are considered infinite.

To get a consistent number of orders, and the time in which those orders arrive, as well as the related due dates, a simulation model was designed using the discrete event simulation software Simio®. It was assumed that the orders start to arrive with the mean time of 20 minutes, and a standard deviation of 5 minutes in a normal distribution. The period in which the orders arrived was from Monday 0:00 until Wednesday 23:59. The simulation makes the decision for each order by choosing the cheapest way for the next step without planning ahead, it does not consider the interaction between orders. Using this logic, the time in which the orders arrive at the client are saved and later used as the due date for the graph.

4.1 Results

With the objective of reducing the total cost of the presented problem, an algorithm was implemented, which uses the algorithms developed by Kennington and Helgason (1980). The proposed method was prototypically implemented in Pascal and applied to the test scenario on an Intel Core 2.8 GHz CPU with 12 GB RAM. The computational time to run each scenario was two seconds, as opposed to twenty seconds from the simulation. The performance comparison between the simulation and the graph model are shown in Figure 8. Twenty scenarios with varying arriving time and due dates were considered.

Figure 8 – Results

The integrated scheduling based on graphs presents superior performance, in terms of operational costs, when compared to the results obtained using simulation. This result was expected due to the fact that the graph model runs an algorithm which seeks the optimum solution in terms of costs. The comparison between both approaches was made in order to situate the cost obtained with the integrated scheduling based on graphs with the average cost of a production and transports system without any specific scheduling rule, i.e. where scheduling decisions are taken randomly. Thereof, as we intended to demonstrate, the use of the proposed graph-based approach to represent and address the integrated scheduling of production processes and transport operations along global supply chains is feasible.

This approach still needs to be compared with other optimization heuristics. Since the proposed approach turns the scheduling problem into a shortest path problem, it is expected to run faster than other heuristics, since shortest path problems usually are solved faster. The quality of the solution proposed by this approach may also need to be tested, and it is expected to be a little lower than other heuristics, since the proposed model tries to make as many mathematical simplifications as possible, sacrificing some quality in favour of computational time.

5 FINDINGS AND FUTURE RESEARCH

This paper introduced a heuristic approach for the scheduling of intermodal transport operations based on graph theory. While an intuitive way of formulating the task by means of a graph would lead to an NP complete problem, the complexity could be reduced to a shortest path problem, solvable in polynomial time, by building a time-dependent graph.

The results indicate that the graph theory can be a good subject of study in order to achieve better results in the global supply chain problems. The time dependent graph can be used to turn several global supply problems, with very few adaptations, into multiple shortest path problems, one for each order. Thus, solving the graph model would lead to a good solution of the integrated scheduling of global supply chains (an originally NP-Complete problem) in reasonable computational time. Finally, since the model uses only time, capacity and cost as variables, a great variety of other similar scheduling problems can be solved with the proposed approach. Future research concerning graphs can develop more complex scenarios and adapt the standard approach for better suiting those scenarios. In addition, comparisons between the proposed approach and other heuristic or exact procedures capable of solving the integrated scheduling of production and transport processes along global supply chains problem could be proposed.

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