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Graph-based integrated production and intermodal transport scheduling with capacity restrictions

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ABSTRACT

Global manufacturing supply chains may link subsequent production facilities by intermodal transport operations, which are characterised by long transport times, scarce transport capacities and a given time table. Consequently only an integrated scheduling of production and intermodal transport operations may be able to materialise the competitive advantage of such a supply chain in terms of total cost and on time delivery reliability. The execution of this planning task is challenging for both supply chain professionals and scientists, since the underlying planning problem is NP-hard. This paper details a new methodological approach for solving integrated production and transport scheduling problems based on a graph, which allows a reformulation of the scheduling problem as a shortest path problem for each job, which can be solved in polynomial time. The proposed method is applied to a supply chain scenario, which contains a manufacturing facility in Brazil and shipments to customers in Germany. The obtained results show that the approach is suitable for the scheduling of large-scale problems and can be flexibly adapted to different real-world scenarios.

Introduction

Global manufacturing supply chains may consist of production facilities around the globe and serve local markets at the same time. Due to the large scale of such networks, transport processes become more vital for the network performance. This is due to increasing transport times and scarce transport capacities. In addition, some modes of transport, e.g. air and maritime transport, may follow a given time table, which also limits the flow of material. Christopher [2] argues that effective and efficient interfaces among partners should be fostered in order to materialise the supply chain competitiveness. On the operational planning level this may require an integrated scheduling of production and transport operations, which pursues the minimisation of the total cost and the on time delivery of customer orders [3]. However, professionals and scientists consider the scheduling of production and intermodal transport operations usually in a separated way, since the underlying integrated planning problem is NP-hard. This paper contributes to this challenging planning problem by detailing and demonstrating the applicability of a graph-based scheduling approach, which was initially published by [1].

Models to better understand and evaluate complex large-scale supply chains are being developed and studied. Different modelling paradigms can be successfully used to describe a supply chain, and better conclusions can be drawn from the comparison between these paradigms [4]. However, a comprehensive and adaptable method is missing (cf. [5]). Due to growing globalisation, designing and scheduling of intermodal transport systems are becoming increasingly relevant [6]. In order to improve decision making in dynamic and competitive global environments, the utilisation and availability of logistics systems must be better considered by production planning and control systems [7,3,8]. Therefore, there has been a growing research interest in scheduling problems, especially for transport and production planning [9,10]. Furthermore, complex problems such as transport routeing in supply chains [11] as well as capacity allocation and scheduling in supply chains [12] enclose important research challenges.

Currently, the scheduling of production and transport processes in manufacturing supply chains is done separately. However, these processes are interdependent, so that an integrated consideration of information and material flows may enable improvements of the overall supply chain performance [13,14]. The reason for this is

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that the combination of an optimum of the individual production scheduling problem and an optimum of the individual transport scheduling problem does not necessarily lead to a global optimum, if both systems are considered together. Different approaches for the integrated scheduling of a supply chain, involving production and intermodal transport scheduling have been proposed (cf. [13] or [15]). The integration and synchronisation of production and distribution scheduling is addressed in the literature for different supply chain scenarios [16–18]. Nevertheless, most of the proposed approaches focus on the tactical planning level of supply chains. However, an efficient operation of a supply chain also requires planning methods for the operational level, which includes the assignment of jobs to specific resources such as machines or transport devices. For practical applications an intuitive approach is preferable, in order to generate comprehendible decisions and to achieve a high acceptance by the executing personnel. Therefore, the use of graph theory is a promising approach for dealing with integrated scheduling problems [19]. Graph-based approaches have been employed to solve scheduling problems in different settings. The disjunctive graph proposed in [20] became a popular tool used for describing instances of the job shop scheduling problem. This graph representation has been studied intensively also regarding time and memory efficiency [21]. Other approaches use graphs for the construction of robust schedules [22] or for the optimisation of special cases such as cyclic scheduling problems with time constraints [23]. Graph theory can also be used to investigate the combination of different optimisation problems [24], especially regarding manufacturing and transport scheduling problems [25].

This paper considers the scheduling of production systems, which can be modelled as hybrid open flow shops and the scheduling of capacitated intermodal transport systems in an integrated way. The intermodal transport may comprise flexible land transport by truck and maritime transport running a given timetable. In particular, a heuristic scheduling approach is detailed, which is based on a graph of all possible production and transport operations, which are within a defined interval of time. This allows for a reformulation of the production and transport scheduling problem (PTSP) as a shortest path problem for each job, which can be solved in polynomial time. The paper presents a generic construction scheme for the graph, which models production and transport operations in the same way. The nodes of the graph are time-dependent and represent the beginning and end of operations. The edges between the nodes represent the operations. They are capacity and cost weighted. A schedule can be computed for a set of jobs, in which each job has to be delivered to a certain destination node before his due date. In addition, each job has specific capacity requirements and can only be processed by resources, i.e., edges, which offer sufficient capacity. The complete schedule is determined in an iterative approach. In each iteration step, the optimal path for one of the jobs is computed as follows. After the choice of a specific job, the graph is temporarily reduced to all edges, which provide sufficient capacity for the processing of the considered job. This way, the derived sub-graph contains only feasible edges for the job and the optimal path can be determined by solving a shortest path problem.

The remainder of the paper is based on the methodological approach for solving the PTSP, which is sketched in [1]. In comparison to [1], the paper details the building blocks of the algorithm and presents a comprehensive pseudo-code of the algorithm. In addition, the complete formulation of the equivalent mathematical program is given. The solutions of the program serve as benchmark for the complementing computational testing, which considers larger problem instances in order to analyse the development of computation time with a growing number of jobs to be scheduled. Section 'Graph-based heuristic scheduling scheme' describes the entire methodological approach. In particular, the modelling scheme of manufacturing and intermodal transport operations of a supply chains as a graph is discussed. Based on this, the heuristic scheduling scheme is presented, which transforms the PTSP into a set of shortest path problems. Section 'Computing exact solutions' formulates the equivalent mathematical program of the considered PTSP as a mixed-integer program. The implemented program can provide benchmark solutions for small problem instances. Section 'Computational analysis' applies both the developed graph-based scheduling approach and the mathematical program to instances of different size of a supply chain scenario with a manufacturing facility in Brazil and shipments to customers in Germany by land and maritime transport. A subsequent analysis investigates solution quality and solution time. Finally, Section 'Conclusions' draws some conclusions of the presented methodological approach and points out some directions for future research.

Graph-based heuristic scheduling scheme

This section details the methodological approach for the integrated scheduling of production and intermodal transport operations. The approach gives special attention to a common modelling procedure for production and intermodal transport operations. This includes road transport by trucks, which is typically the initial and final transport mode between consecutive facilities and has a high flexibility in terms of availability. In contrast to this maritime or air transport may bridge intercontinental distances and follow a given time table, which can be hardly adapted to short-term operational needs. This differentiation holds as well for the capacity of the different transport modes, i.e., increasing or decreasing the number of employed transport devices can adjust the capacity of road transport. This is usually not applicable in the case of time-table-based transport modes, such as maritime or air transport. In the following the building blocks of the graph are described before the heuristic scheduling scheme is detailed.

Building blocks of the graph

The graph G=(V,E) consists of a set of nodes V and a set of edges E, in which each edge represents a connection between a pair of nodes. In this modelling approach, the nodes are located in the x/y-plane, in which the x-axis represents time t and the y-axis represents locations i. The continuous time t is discretised, e.g. into shifts of 8 h or any other process relevant time interval. A location i can either be a physical place along the production or transport processes, such as a port, the final customer or a storage level between two consecutive manufacturing steps. Thus, a node v of the graph can be expressed as a pair (t_v,i_v) of a location i_v and a point in time t_v. Fig. 1 shows a basic example of a graph with one location. The blue arrows, which connect the location at its different points in time from the left to the right side represent storage at location i for 3 shifts.

Each location along the supply chain is represented as a location on the vertical axis. Hence, the transport of cargo is the movement

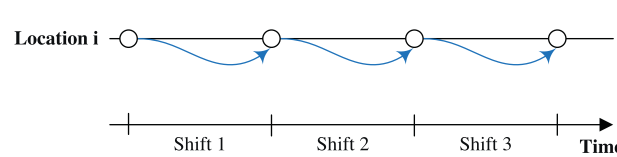

Fig. 1. Trivial graph with one location.