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**Pengembangan Model Penjadwalan Barge-to-Crane Bi-Objektif untuk Minimasi Makespan dan Emisi Karbon
pada Proses Transshipment Batubara: Studi Kasus Perusahaan Tambang**
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# INTISARI

Pada fasilitas *transshipment* batubara berbasis sungai, keputusan alokasi dan urutan pemuatan tongkang (*barge*) pada *floating crane* menentukan waktu penyelesaian pemuatan kapal (*makespan*) sekaligus lamanya *barge* berada di fasilitas, yaitu selama menunggu giliran dan selama dimuat. Selama periode tersebut, kapal tunda (*tugboat*) yang menarik *barge* tetap beroperasi dan menghasilkan emisi karbon. Model penjadwalan *barge-to-crane* sebelumnya memperlakukan satu jam waktu tunggu secara seragam bagi seluruh *barge*, padahal *barge* berkapasitas lebih besar ditarik *tugboat* berdaya lebih tinggi sehingga menghasilkan emisi per satuan waktu yang lebih besar. Penelitian ini mengembangkan model *Mixed Integer Linear Programming* bi-objektif yang meminimalkan *makespan* dan estimasi emisi $CO_2$, diformulasikan sebagai *Unrelated Parallel Machine Scheduling Problem* dengan batasan *release time*, kesiapan *crane*, dan *non-overlap*. Data teknis *tugboat* tidak dapat diakses dalam penelitian ini, sehingga laju emisi diestimasi melalui klasifikasi *Natural Breaks (Jenks)* atas 41 observasi tonase *barge*, fungsi linear kebutuhan daya *tugboat*, dan kerangka estimasi emisi *bottom-up*. Model diselesaikan menggunakan metode *epsilon-constraint* dengan *exact solver* pada data historis lima kapal. Klasifikasi menghasilkan tiga kelas *barge* dengan estimasi laju emisi fase *idle* sebesar 21,8; 79,7; dan 126,7 kg $CO_2$ per jam. Hasil optimasi menghasilkan 11 solusi *non-dominated* dengan satu hingga empat alternatif per kapal dan rata-*rata marginal emission penalty* sebesar 127,05–531,55 kg $CO_2$ per jam pengurangan *makespan*. Tambahan emisi cenderung meningkat tajam ketika solusi mendekati *makespan* minimum. Analisis sensitivitas dengan penskalaan seragam laju emisi ±20% dan ±30% menunjukkan bahwa himpunan solusi *non-dominated* dan nilai *makespan*-nya tidak berubah, sedangkan besaran emisi berubah sebanding dengan faktor skala. Struktur solusi tersebut bersyarat pada perbandingan laju emisi antarkelas hasil estimasi. *Makespan* minimum model identik dengan hasil reproduksi model sebelumnya. Dibandingkan kebijakan *First-In-First-Out* aktual, solusi *makespan* minimum memperbaiki *makespan* pada empat dari lima kapal hingga 22,82%. Kontribusi utama penelitian ini terletak pada penyediaan informasi konsekuensi emisi dari setiap alternatif jadwal bagi pengambil keputusan.

**Kata kunci:** penjadwalan *barge-to-crane*, *unrelated parallel machine scheduling*, emisi karbon, *epsilon-constraint*, *transshipment* batubara

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# *ABSTRACT*

*At river-based coal transshipment facilities, decisions on the allocation and sequencing of barges to floating cranes determine both the vessel loading completion time (makespan) and the time each barge spends at the facility, both waiting for its turn and being loaded. Throughout this period, the tugboat towing the barge remains in operation and generates carbon emissions. Existing barge-to-crane scheduling models treat one hour of waiting time as uniform across all barges, although larger-capacity barges are served by higher-powered tugboats and therefore generate greater emissions per unit of time. This study develops a bi-objective Mixed Integer Linear Programming model that minimises makespan and estimated $CO_2$ emissions, formulated as an Unrelated Parallel Machine Scheduling Problem with release time, crane readiness, and non-overlap constraints. As tugboat technical data could not be accessed in this study, emission rates are estimated through a Natural Breaks (Jenks) classification of 41 barge tonnage observations, a linear tugboat power function, and a bottom-up emission estimation framework. The model is solved using the epsilon-constraint method with an exact solver on historical data from five vessels. The classification yields three barge classes with estimated idle-phase emission rates of 21.8, 79.7, and 126.7 kg $CO_2$ per hour. The optimisation yields 11 non-dominated solutions, with one to four alternatives per vessel and average marginal emission penalties ranging from 127.05 to 531.55 kg $CO_2$ per hour of makespan reduction. Additional emissions tend to increase sharply as solutions approach minimum makespan. A sensitivity analysis applying uniform scaling of ±20% and ±30% to all emission rates shows that the set of non-dominated solutions and their makespan values remain unchanged, while emission magnitudes change in proportion to the scaling factor. This solution structure is conditional on the estimated ratios of emission rates between barge classes. The minimum makespan of the proposed model is identical to that obtained by reproducing the previous model. Compared with the current First-In-First-Out policy, the minimum-makespan solution improves makespan in four of five vessels by up to 22.82%. The main contribution of this study lies in providing information on the emission consequences of each scheduling alternative to decision makers.*

***Keywords:*** *barge-to-crane scheduling, unrelated parallel machine scheduling, carbon emissions, epsilon-constraint, coal transshipment*