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論文の内容の要旨

In recent years, the advancement of computer processing (hereafter referred to as "machines"), such as deep learning, other advanced algorithms, and increased processing power, make more attention to further sophistication in decision-making through collaboration between humans and machines that take advantage of the features of each. In the research field of knowledge science as well, knowledge creation through mutual complementation between humans and machines has become an important research topic in the digital age. Most of the recent decision-making research using machines has focused on automation and support for problems with a single entity or in which there is a hierarchical relationship among multi-entity, such as superiors and subordinates, and where prioritization among the objectives is possible. Decision-making support for multi-objective and multi-entity situations has been a challenging area for the future. In this study, we focus on multi-objective, multi-entity decision-making. Then, in a multi-echelon inventory problem, a specific example of such a problem, we propose and implement a new collaborative process between humans and machines to clarify the effects of machines and collaborative processes on human decision-making.

According to Simon (1960), decision-making can separate into three processes: information, design, and selection activities. Schorsch et al. (2017) suggest information activities such as information gathering and monitoring, which are highly reproducible from historical data, and design activities such as optimization calculations and simulations should be handled by machines, while the main parts of selection activity should be in charge by humans, such as consideration of future scenarios and knowledge creation, which are less reproducible from historical data, and also final verification and judgment. Referring to these previous studies, we proposed a practical collaborative process. In our process, information and design activities are performed by machines mainly. And selection activities are performed by humans and machines interactively, converting multiple objectives from objective functions to constraints step by step to make decisions on a multi-echelon inventory allocation problem. Then, we developed the machine functions for information, design, and selection activities in the proposed process, as well as confirmed the effectiveness of the proposed human-machine collaborative process.

Firstly, we confirmed by the game theory that the proposed process enables multiple entities to reach an agreement. Then, we applied the proposed process to practical situations, conducted unstructured interviews with users, and analyzed the results using the thematic analysis method to confirm that it is possible to rational decision-making effectively and rapidly by the proposed process.

Secondly, we developed a simulation-based optimization method for a multi-echelon inventory problem that can derive a highly optimal solution in a shorter computation time than the genetic algorithm (GA), which is considered the most common method. The constrained Bayesian optimization approach employed in this study outperforms both GA and penalty-based Bayesian optimization in terms of optimality and computational efficiency.

Thirdly, the maritime transportation arrival prediction is the input data for the inventory allocation calculation and significantly impacts the calculation optimality. So, we developed a method that predicts more accurately than the Dijkstra method and A* algorithm, which have been the mainstream machine approaches in the past. There are cases where vessels do not arrive at the destination port as planned

due to changes in weather conditions along the route. On the other hand, previous studies failed to consider future weather conditions. So, we proposed an arrival prediction method that considers future weather conditions in two steps: (1) route calculation and (2) navigation speed calculation, using a Bayesian learning approach. The prediction accuracy was 90%, superior to 62% in the previous study.

Finally, we extracted the five points as follows that should be kept in mind when considering the collaborative process between humans and machines in decision-making and consensus-building support in multi-objective, multi-entity situations, based on the analysis with the game theory and with thematic analysis of the interview result from several perspectives such as negotiation studies, the knowledge creation through mutual complementation between humans and machines and the trust from human to machine. (1) A process in which each actor gains more by adopting a cooperative strategy than by betraying one. (2) A process in which machines play the role of mediator and lead to principle-based negotiation. (3) Finding and expanding the areas where the machine can be more precise and delegate more authority than humans and entrust them to the machine. (4) Machine evaluates and optimizes the combination of multiple people's knowledge. (5) In areas where machines are in charge, establish an introduction step and mechanism for people to trust machines.

As described above, in this study, we proposed a collaborative process between humans and machines for multi-objective, multi-entity decision-making, which had been a future challenge area, using the multi-echelon inventory problem as an example. Then we confirmed the effectiveness of the proposed process and demonstrated the key points for designing decision-making processes for other similar situations.

Keywords: Human-machine collaboration, Multi-objective and multi-entity decision-making, Multi-echelon inventory problem, Simulation-based optimization, Prediction of maritime transportation

論文審査の結果の要旨

昨今，膨大なデータを扱う計算機能力の向上とともに人工知能や最適化技術が革命的に進歩・普及し，ビジネスの現場において人間と機械がどのように協働（Human-Machine Collaboration）するかは，知識科学の最も重要な研究課題の１つである．本論文では，複数目的で複数主体による意思決定が必要な多段階在庫配置問題において，人間と機械（知的な情報システム）の新しい協働プロセスおよびシステムを提案・実装し，それをグローバル製造業の現場で適用・評価したものである．

本研究では，多段階在庫配置問題において，情報活動（データ収集・分析・予測）と設計活動（最適化）を機械主体で行い，複数主体（異なる企業の人間）と機械が対話型で複数目的を制約条件に段階的に変換し，選択活動（意思決定）を行う実践的な協働プロセスを提案・実装した．提案プロセスの妥当性をゲーム理論により裏付けるとともに，実務に適用した上で利用者へのインタビューを実施し，その有効性を確認した．従来から，機械を用いた意思決定支援の研究が行われてきたが，その多くは単一主体もしくは複数主体であっても目的間の優先度付けが可能な問題が対象であり，複数目的・複数主体の意思決定・合意形成支援は今後の挑戦的研究課題とされてきた．この挑戦的研究課題に対し，実務に適用可能な新しい協働プロセスを提案し，グローバル製造業で適用・評価している点は新規性・有用性の面で高く評価できる．

また、提案プロセスにおいて機械が担う２つの重要な技術（多段階在庫配置最適化技術，海上輸送時間予測技術）を新しく開発している．前者は，従来手法より短い計算時間で最適性が高い解を導出可能なシミュレーションベース最適化技術であり，後者は，多段階在庫配置最適化に大きな影響を与える海上輸送におけるベイズ学習アプローチによる高精度到着時間予測技術である．これらの開発技術は学術的新規性のみならず実務での有効性が確認されており，情報科学への貢献の視点でも評価できる．

本論文の考察では，提案プロセスの実務での適用を踏まえて，複数目的・複数主体の場面での意思決定・合意形成支援における人と機械の協働プロセスを検討する上で抑えるべき要諦を，交渉学，人と機械の相互補完による知識創造，人の機械への信頼（トラスト）の３つの視点で分析しており，人と機械の協働に

関する知識科学の研究への示唆も極めて大きい．

以上，本論文は，知識科学の最重要な研究課題の１つであり，挑戦的研究課題とされてきた複数目的・複数主体の場面での人と機械の協働プロセスを提案した点で学術的貢献があるとともに, 既にグローバル製造業の現場で適用・評価している点で実務的にも大きな貢献があると思われる．よって，博士（知識科学）の学位論文として十分価値のあるものと認めた．