様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　６ 年　６ 月 ２５ 日現在

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研究種目：基盤研究(C)（一般）
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研究課題名（和文）Resilience in the Facility Location Problem: Theory and Practice

研究課題名（英文）Resilience in the Facility Location Problem: Theory and Practice

研究代表者
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研究成果の概要（和文）：研究では施設配置の最適化を目指し、災害時にも信頼性の高いサービスを提供することに焦点を当てました。私たちは「部分的な頑健性」の概念を導入し、コスト効率と災害耐性をバランスさせることを目指しました。私たちのアプローチは、頑健性と回復可能性のソリューションを組み合わせ、災害後に95%の人々がサービスにアクセスできることを保証しました。国際的な協力を通じて、このコンセプトを形式化し、効率的なアルゴリズムを開発し、使いやすいソフトウェアプログラムを作成しました。この研究は主要なジャーナルに掲載され、都市計画や災害対応における実践的な利点を示し、理論と実際の結びつきを強化しました。

研究成果の学術的意義や社会的意義
この研究プロジェクトは、「部分的な頑健性」の導入により、都市インフラの耐災性を向上させる画期的な方法を提供します。通信インフラの最適化だけでなく、災害対応や医療物流にも応用可能です。公開されたソフトウェアツールの開発は、都市計画の透明性とアクセス性を促進し、コミュニティの強靭さと準備力を向上させます。

研究成果の概要（英文）：Our research tackled the problem of facility location. We focused on optimizing facility deployment like cell towers to ensure reliable service, even during disasters. We introduced the notion of "partial robustness," balancing cost efficiency with disaster resilience. Our approach combined robust and recoverable solutions, ensuring that a significant portion of the population retains access to services (e.g., 95%) post-disaster. Collaborating globally, we formalized this concept, developed efficient algorithms, and created user-friendly software program. Publications in top conferences and journals validated our findings, highlighting practical benefits for urban planning and disaster response. This research bridges theory with real-world impact, offering cost-effective solutions for resilient infrastructure deployment.

研究分野：Systems Resilience

キーワード：Systems resilience　Multiagent systems　Knowledge representation　Artificial Intelligence　Facility location　Robustness

１．研究開始当初の背景

The challenge of facility deployment involves strategically situating a variety of facilities (such as health centers, antennas, schools, and shelters) on a map to maximize service coverage while minimizing deployment costs. This issue is especially crucial for mobile phone operators seeking to establish cell towers in urban areas, aiming to optimize wireless network coverage across the population while keeping deployment costs low.

Typically, conventional AI systems develop *efficient* solutions, which prioritize maximizing the coverage-to-cost ratio but overlook potential external events and natural disasters that could disrupt facility functionality. In the worst-case scenario, damage to even a single facility post-deployment could lead to a sudden and significant decline in service coverage. Therefore, the central question we tackled in this project was: how can we deploy facilities that are not only cost-efficient but also ensure a certain level of service quality during the initial deployment phase (phase 1), withstand disasters (phase 2), and facilitate swift and cost-effective recovery afterward (phase 3)?

Several existing studies have attempted to tackle this problem, leading to the development of two complementary solutions known as *robustness* and *recoverability*. Each solution has its own merits and drawbacks: a robust solution ensures system functionality post-disaster and can be computed efficiently but comes with prohibitively high deployment costs. Conversely, a recoverable solution allows for more cost-effective deployment but is computationally challenging, if not impractical, and offers no guarantees during the disaster phase. Our objective was thus to strike a balance between these two concepts and propose a novel notion of *partial robustness* that combines the benefits of both robustness and recoverability while mitigating their drawbacks.

２．研究の目的

The primary research objectives focused on formalizing and investigating a trade-off notion that combines the aspects of robustness and recoverability for practical purposes. The goal was to ensure a certain percentage of population coverage, even under unfortunate circumstances of a specific scale. This notion aimed to be more realistic than previous ones by reflecting real-world situations: it involved minimizing the impact of potential disasters on the system during the disaster phase (e.g., restricting service loss to no more than 5% of the total population after some facilities are damaged), thereby reducing the prohibitive cost associated with introducing excessive redundancy in the initial deployment phase. The objectives were divided into several steps:
- To formalize this new notion within the framework of Coalition Formation (CF): since CF is a widely used formalism capable of representing a broad range of systems, our notion would be directly applicable to other applications, such as shift scheduling generation or disaster medical assistance team (DMAT) deployment.
- To investigate the computational complexity of finding a deployment solution according to this new notion: this technical task involved identifying the inherent difficulty of the problem, regardless of any algorithm used to solve it. This step is necessary before designing specific algorithms and includes demonstrating reductions from existing problems whose complexity is known to the revised deployment problem.
- To design dedicated algorithms to solve the problem and compare them with existing ones implementing the previous notions of robustness and recoverable deployment solutions.
- To create a broad class of benchmarks modeling elevation maps with population density and test the algorithms on these benchmarks.
- To develop publicly available software program that allows users to generate populated maps based on certain parameters artificially and assess how partial robust deployment solutions appear on these artificially generated instances.
- On a broader scale, to provide a deeper understanding of how changes affect evolving systems and how to integrate those changes into the system so that it accurately understands and correctly models the world it represents.

３．研究の方法

To achieve the objectives, we employed a multi-faceted research approach combining theoretical analysis, algorithm design, and practical implementation:
- Theoretical Analysis: We formalized the new notion of partial robustness within the framework of Coalition Formation (CF). This involved defining the problem space, developing theoretical models, and analyzing the computational complexity of the proposed solutions.
- Algorithm Design: Based on the theoretical foundation, we designed specific algorithms aimed at efficiently finding partially robust deployment solutions. These algorithms were compared with existing ones to evaluate their performance and effectiveness.
- Benchmark Creation: We developed a broad class of benchmarks that model various real-world scenarios, including elevation maps with population density. These benchmarks were used to test and validate the proposed algorithms.
- Software Development: A software tool was created to generate populated maps based on user-defined parameters. This tool was made publicly available to facilitate further research and practical application of the proposed solutions.
- Collaboration and Dissemination: The research was conducted in collaboration with several academic institutions, including the National Institute of Informatics (NII) in Tokyo, Delft University of Technology (TU Delft) in the Netherlands, and the Lens Computer Science Research Center (CRIL) in France.

Findings were disseminated through publications in leading Artificial Intelligence forums and conferences, resulting in multiple high-impact publications: two publications in the premier journal of Autonomous Agents and Multi-Agent Systems, as well as six publications in international venues (KR'20, AAMAS'21, AAAI'22, KR'22, KR'23 * 2), all of which hold an A* ranking according to the CORE ranking system.

４．研究成果

A - Summary of Results Illustrated with an Example:

The figure below illustrates a facility location problem, where the goal is to deploy a set of facilities on a populated map to maximize population coverage while minimizing deployment costs. Imagine each facility as a cell tower that can be placed anywhere on the map. The larger the coverage radius of the cell tower, the higher the cost; for simplicity, a tower with a coverage radius of X has a deployment cost of X.

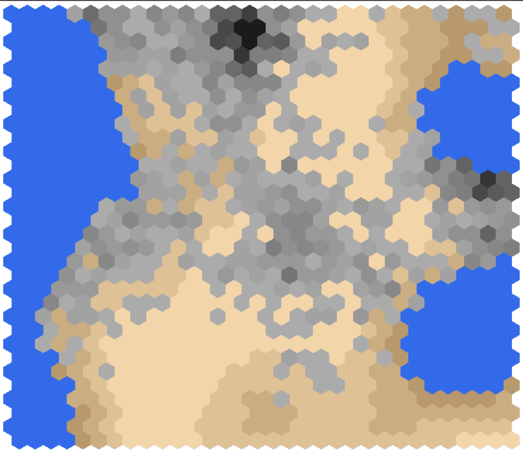
Map (a): The top-left map shows a populated area with no cell towers. Water is blue, land and mountains are white, and gray scales represent population density (darker means more densely populated). The objective is to deploy cell towers, so everyone has network access.

Map (b): The top-right map shows the most *efficient* solution, a deployment solution costing 63. This is the least expensive way to provide full network coverage. However, if the two large cell towers in the north and east (both with a radius of 5) fail, a significant portion of the population will lose connectivity.

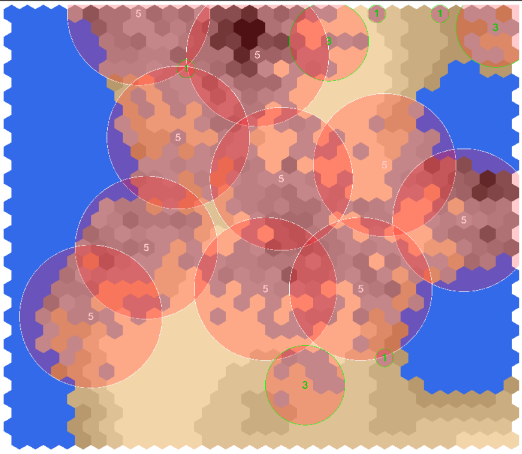
Map (c): The bottom-left map shows a *2-robust* solution, meaning if any two towers fail, the network still covers everyone. This solution is very expensive, costing 194, and may be unnecessary since tower failures are rare.

Map (d): The bottom-right map shows a *(2, 90%)-partially robust* solution, corresponding to our new concept, costing 95. If any two towers fail, 90% of the population remains connected in the worst-case scenario. This solution is advantageous because it balances cost (95) and coverage, ensuring minor failures do not cause major connectivity issues. It is less risky than the efficient solution (b) and much cheaper than the 2-robust solution (c).

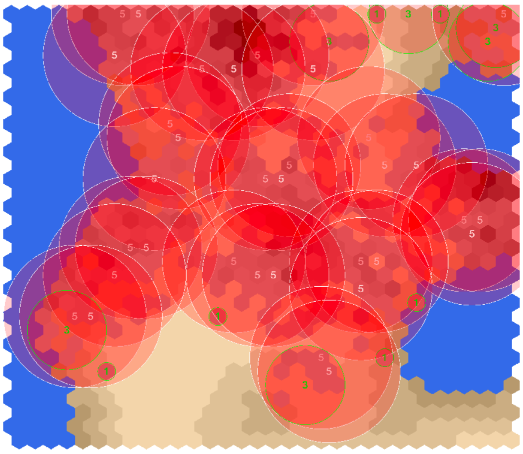
Our research formalized the concept of partial robustness, evaluated its performance across various scenarios, and compared it with existing notions of efficiency, robustness, and recoverability. We demonstrated that partial robustness offers a valuable trade-off between deployment cost, coverage, and computational complexity.



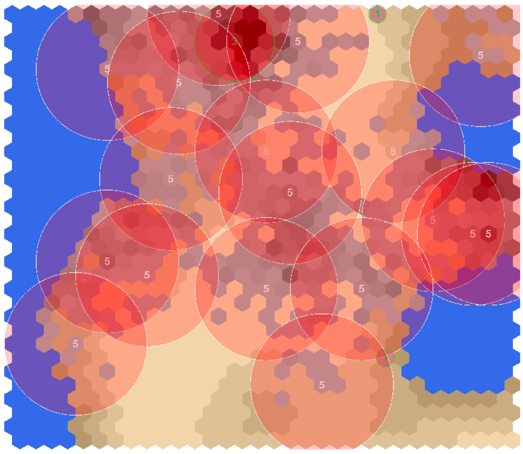
(a) A populated map.



(b) An optimal efficient cell tower deployment (total deployment cost = 63)



(c) An optimal 2-robust cell tower deployment (total deployment cost = 194)



(d) A satisfactory $\langle 2, 90\% \rangle$-partially robust cell tower deployment (total deployment cost = 95)

B - Detailed History of Research Achievements:

- FY2020: Initial Findings and First Publications

-> Introduced partial robustness in multi-agent systems and team formation.
-> Analyzed computational complexity, finding it intermediate between robustness and recoverability.
-> Developed and implemented a first algorithm for computing partially robust teams.
-> Demonstrated that partial robustness offers a balanced trade-off in terms of deployment cost, coverage efficiency, and recovery cost.
-> Main results published at AAMAS'21 [1] and recognized as a premier paper.
-> Published previous results on a probabilistic version of resilience in Coalition Formation [2], as well as a new theoretical study of resilience and change at KR'20 [3].

Related Publications:

[1] Nicolas Schwind, Emir Demirović, Katsumi Inoue, Jean-Marie Lagniez. 'Partial Robustness in Team Formation: Bridging the Gap between Robustness and Resilience'. AAMAS'21, pages 1151-1162. London, United Kingdom, May 2021 (online).
[2] Nicolas Schwind, Tenda Okimoto, Katsumi Inoue, Katsutoshi Hirayama, Jean-Marie Lagniez, Pierre Marquis. On the Computation of Probabilistic Coalition Structures. Autonomous Agents and Multiagent Systems, 35(1):14. March 2021.
[3] Nicolas Schwind, Sébastien Konieczny. Non-Prioritized Iterated Revision: Improvement via Incremental Belief Merging. KR'20, pages 738-747. Rhodes, Greece, September 2020 (online).

- FY2021: Main Algorithm Improvement and Software Development

-> Developed an improved anytime algorithm for resilient team deployment solutions,

improving solution speed and quality.
-> Created software program for generating facility location instances with various parameters.
-> Published theoretical studies on resilience and change at AAAI'22 [4].

Related Publication:
[4] Nicolas Schwind, Sébastien Konieczny, Ramón Pino Pérez. 'On Paraconsistent Belief Revision in LP'. AAAI'22, pages 5879-5887. February 2022 (online).

- FY2022: Comparative Analysis and Software Release
-> Compared findings with coalition structure generation, set cover, and facility location.
-> Published a journal paper [5] and released software program for generating facility location instances [6].
-> Created a benchmark set used by the SAT competition community [7].
-> Published research on resilience and knowledge representation at KR'22 [8].

Related Publications and Software:
[5] Nicolas Schwind, Emir Demirović, Katsumi Inoue, Jean-Marie Lagniez. 'Algorithms for Partially Robust Team Formation'. Autonomous Agents and Multiagent Systems, 37(2):22, April 2023.
[6] TP map solver software tool (co-developed with Prof. Jean-Marie Lagniez, CRIL). URL: https://github.com/nicolas-schwind/TF-map-solver
[7] Nicolas Schwind, Emir Demirović, Katsumi Inoue, Jean-Marie Lagniez. 'SAT Benchmarks for the Robust Team Formation Problem'. SAT Competition 2022, University of Helsinki, 2022.
[8] Nicolas Schwind, Sébastien Konieczny, Ramón Pino Pérez. 'On the Representation of Darwiche and Pearl's Epistemic States for Iterated Belief Revision'. KR'22, pages 320-330. Haifa, Israel, August 2022.

- FY2023: Theoretical Exploration and Future Foundations
-> Investigated theoretical aspects of change and resilience, focusing on integrating new information into formal systems.
-> Identified limitations in current frameworks and introduced new rationality principles for iterated belief revision.
-> Proposed practical strategies for belief update and presented findings at KR'23 [9, 10].

Related Publications:
[9] Nicolas Schwind, Sébastien Konieczny, Ramón Pino Pérez. 'Iteration of Iterated Belief Revision'. KR'23, pages 625-634. Rhodes, Greece, September 2023.
[10] Eduardo Fermé, Sébastien Konieczny, Ramón Pino Pérez, Nicolas Schwind. 'Credible Models of Belief Update'. KR'23, pages 252-261. Rhodes, Greece, September 2023.

In FY2023, we concluded the project by laying a strong foundation for future research on systems resilience and change, ensuring a robust framework for integrating new information into formal systems.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　2件／うちオープンアクセス　0件）

１．著者名 Nicolas Schwind, Emir Demirovic, Katsumi Inoue, Jean-Marie Lagniez	４．巻 37(2):22
２．論文標題 Algorithms for partially robust team formation	５．発行年 2023年
３．雑誌名 Autonomous Agents and Multi-Agent Systems	６．最初と最後の頁 1-45
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s10458-023-09608-7	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Nicolas Schwind, Tenda Okimoto, Katsumi Inoue, Katsutoshi Hirayama, Jean-Marie Lagniez, Pierre Marquis	４．巻 35(1):14
２．論文標題 On the computation of probabilistic coalition structures	５．発行年 2021年
３．雑誌名 Autonomous Agents and Multi-Agent Systems	６．最初と最後の頁 1-38
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s10458-021-09498-7	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計6件（うち招待講演　0件／うち国際学会　6件）

１．発表者名 Nicolas Schwind, Sebastien Konieczny
２．発表標題 Non-Prioritized Iterated Revision: Improvement via Incremental Belief Merging
３．学会等名 Proc. of the 17th International Conference on Principles of Knowledge Representation and Reasoning (KR'20)（国際学会）
４．発表年 2020年

１．発表者名 Nicolas Schwind, Emir Demirovic, Katsumi Inoue, Jean-Marie Lagniez
２．発表標題 Partial Robustness in Team Formation: Bridging the Gap between Robustness and Resilience
３．学会等名 Proc. of the 20th International Conference on Autonomous Agents and Multiagent Systems (AAMAS'21)（国際学会）
４．発表年 2021年

１．発表者名
Nicolas Schwind, Sebastien Konieczny, Ramon Pino Perez

２．発表標題
On Paraconsistent Belief Revision in LP

３．学会等名
Proc. of the 36th AAAI Conference on Artificial Intelligence (AAAI'22)（国際学会）

４．発表年
2022年

１．発表者名
Nicolas Schwind, Sebastien Konieczny, Ramon Pino Perez

２．発表標題
On the Representation of Darwiche and Pearl's Epistemic States for Iterated Belief Revision

３．学会等名
Proc. of the 19th International Conference on Principles of Knowledge Representation and Reasoning (KR'22)（国際学会）

４．発表年
2022年

１．発表者名
Nicolas Schwind, Sebastien Konieczny, Ramon Pino Perez

２．発表標題
Iteration of Iterated Belief Revision

３．学会等名
Proc. of the 20th International Conference on Principles of Knowledge Representation and Reasoning (KR'23)（国際学会）

４．発表年
2023年

１．発表者名
Eduardo Ferme, Sebastien Konieczny, Ramon Pino Perez, Nicolas Schwind

２．発表標題
Credible Models of Belief Update

３．学会等名
Proc. of the 20th International Conference on Principles of Knowledge Representation and Reasoning (KR'23)（国際学会）

４．発表年
2023年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

Our generation, solving, vizualisation software
https://github.com/nicolas-schwind/TF-map-solver
Our published benchmarks (pp. 74-77)
https://helda.helsinki.fi/bitstream/handle/10138/347211/sc2022_proceedings.pdf

6．研究組織

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研究協力者	コニェツニー　セバスティアン (Konieczny Sebastien)	Research Director	
研究協力者	ラニエ　ジャンマリー (Lagniez Jean-Marie)	Professor	
研究協力者	デミロビッチ　エミール (Demirovic Emir)	Assistant Professor	

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関			
フランス	CRIL-CNRS UMR8188, Artois University	Lens, France		
オランダ	Delft University of Technology	Delft, The Netherlands		