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論文の内容の要旨

The acceleration of global economic and industrial activities has substantially intensified the climate crisis, necessitating urgent and deep decarbonization efforts. While existing research has primarily concentrated on technological advancements in renewable energy and carbon capture as strategies to reduce dependency on fossil fuels, such approaches often overlook the multifaceted nature of achieving a decarbonized society, which requires fostering innovation, collaboration, future-oriented thinking, and changes in awareness and behavior. This dissertation introduces an innovative XaaS (Everything-as-a-Service) roadmapping framework that incorporates Futures Literacy (FL) to support the design of service-oriented systems aligned with decarbonization objectives and consumer well-being. The proposed framework expands the scope of traditional roadmapping by emphasizing ecosystem-wide collaboration and forward-looking perspectives. In contrast to traditional technology or service roadmapping approaches, which typically focus on structured planning within industry-specific boundaries , the XaaS roadmapping framework conceptualizes all value offerings as services and promotes cross-sectoral innovation.

The XaaS framework offers a transformative perspective by reimagining conventional business models into service-based operations. This paradigm shift fosters enhanced flexibility, resource circularity, and organizational adaptability. Grounded in principles of transformative knowledge management , the framework facilitates anticipatory governance , collaborative foresight , and stakeholder co-creation. These capabilities collectively empower organizations to construct dynamic and resilient service roadmaps that can respond to volatile policy landscapes, shifting consumer behaviors, and emergent environmental imperatives, enabling them to make informed decisions.

To evaluate the framework, this study adopted a sequential mixed-methods research design encompassing qualitative and quantitative components. The first phase involved the facilitation of knowledge co-creation workshops with domain experts from the engineering and social infrastructure industries. The workshops progressed through four structured stages: ideation, identification of roadmap components, roadmap drafting, and expert validation. Participants employed FL techniques to develop and prioritize service innovation ideas using criteria such as strategic relevance, desirability, viability, and feasibility. Among the concepts generated, "Carbon Credit Trading-as-a-Service" (CTaaS) was identified as a highly promising initiative due to its potential contributions to environmental sustainability, consumer well-being, and business value.

To overcome knowledge space limitations , topic modeling and patent analysis were employed to extract insights from academic publications (Scopus) and patent data. These analyses informed the construction of a multi-layered

roadmap comprising four core dimensions: policy, market, technology, and service. The roadmap was further refined using a digital collaboration platform, Miro , to enable real-time feedback and consensus building among stakeholders, ensuring both practical relevance and strategic coherence over a timeline from 2023 to 2050.

In the second phase, a scenario-based simulation was conducted using System Dynamics (SD) modeling to investigate the long-term impacts of the CTaaS roadmap on CO_2 emissions in Japan. SD was selected for its robust capacity to model complex system behaviors and interdependencies, particularly those related to sustainability transitions and organizational and social change. The simulation incorporated policy incentives, technological maturity, consumer adoption rates, and financial mechanisms. Three distinct scenarios were analyzed, namely optimistic, neutral, and pessimistic , to assess the robustness of the roadmap under conditions of uncertainty. Results demonstrated that the CTaaS roadmap could significantly reduce national carbon emissions by 2040 , especially under supportive policy regimes and high public engagement. The system dynamics model provided a comprehensive view of the interactions among policy, behavior, and technology.

This research contributes to theory by extending the XaaS paradigm beyond its origins in information technology to encompass environmental and socio-economic systems. Methodologically, it offers a novel integration of foresight practices and service innovation tools through the combined application of Futures Literacy, roadmapping, and system modeling (including System Dynamics). Practically, the framework serves as a strategic guide for policymakers, enterprises, and innovation practitioners seeking to align operational models with the Sustainable Development Goals (SDGs) and climate mitigation targets. Additionally, it underscores the importance of cultivating Futures Literacy as a foundational competency for navigating complex and uncertain sustainability challenges.

In conclusion, the synthesis of XaaS and Futures Literacy within a roadmapping methodology offers a powerful mechanism for systemic innovation. This approach enables organizations to co-create actionable service strategies that not only respond to environmental imperatives but also support long-term societal transformation. Future research could explore the applicability of this framework across diverse industries and cultural contexts to facilitate global pathways toward a decarbonized future.

Keywords: XaaS roadmapping, Decarbonization, Service roadmap, Knowledge co-creation workshop, Futures literacy

論文審査の結果の要旨

本論文は，脱炭素社会の実現に向けたサービス・システムの構築を目指し，Everything-as-a-Service（XaaS）型ビジネスの戦略設計を支援する新たなロードマッピング手法を提案・検証した研究である．従来のテクノロジー中心のロードマップ構想に対し，本論文はFutures Literacy（未来リテラシー）を導入し，未来社会のビジョンを共創的に描き，持続可能性に資するサービスの形成へと導く知識設計の枠組みを提示している点において，極めて独創的かつ実践的意義の大きい内容である．

本論は大きく２つの取り組みで構成されており，はじめはカーボンクレジット取引サービス（CTaaS）を題材に，複数の業界専門家とともに XaaS ロードマップを協働設計する過程を詳細に記述している．未来洞察，特許・文献分析，オンラインホワイトボード（Miro）を用いた視覚ツールの活用など，多様な視点とスキルを有する参加者間での知識の可視化と統合を可能にする工夫が随所に見られる．このプロセスは単なる計画策定にとどまらず，参加者の価値観の共有と学びの場としても機能しており，ロードマップ

を媒介とした知識共創プロセスとして新たなサービス設計の知見をもたらしている．

　後半部では，上記の XaaS ロードマッピングの成果をもとに，システムダイナミクスを用いたシナリオベース・シミュレーションを実施している．政策支援，社会的関心，技術発展といった変数を組み合わせた複数のシナリオ（楽観・中庸・悲観）を想定し，それぞれの条件下で CTaaS の普及や CO_2 排出削減効果を予測した点に，戦略構想の社会実装可能性を実証的に検討しようとする姿勢がうかがえる．因果ループ図やストック＆フローモデルによる構造化により，サービス導入の動態的影響がわかりやすく示されている．

　特筆すべきは，本研究が持続可能性に向けた社会において，脱炭素という共通課題に対して，参加者が未来に向けた知性を持ち寄り，集合的に構想と判断を形成していく実践を促す枠組みを提供していることである．この営みは，知識を蓄積・分析するだけでなく，実践者の内発的動機や関係性を活かして共創するという，新たな知識経営の在り方を体現しており，知識科学分野における理論的・方法論的貢献として高く評価できる．

　以上の理由から，本論文は XaaS 型サービスの価値共創と持続可能な社会形成に向けた知識設計を統合的に示すものであり，博士（知識科学）の学位論文として十分に価値あるものと認められる．